International Workshop
on

Underwater Welding of Marine Structures

December 7-9, 1994
New Orleans, Louisiana, U.S.A.

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Front Cover Photograph:
Repair of Amoco Montrose Platform, North Sea (1990). Comex welder working on sleeve repair. (Courtesy of Dr. S. Ibarra, Amoco Corporation Research.)

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EXECUTIVE SUMMARY

During the past 25 years, underwater welding has established itself as a viable fabrication and repair technology. Not only "old" techniques have been improved, new techniques which include hyperbaric, habitat and wet processes have been developed. Parallel to the technological development, the understanding of the fundamentals of underwater welding has also developed significantly in the last 15 years. As such, the 1994 International Workshop on Underwater Welding of Marine Structures in New Orleans, Louisiana was very timely. Considering that the previous workshop of a similar nature was held in 1985 at the Colorado School of Mines, Golden, Colorado, it is time for the experts in the field of underwater welding to again gather and discuss the status of underwater welding.

The timely nature of the workshop was certainly demonstrated by the supportive addresses presented by government leaders, representatives from the regulatory and certification agencies, and management of several international oil companies. The status report of underwater welding which included materials issues, processing updates, deep water applications, equipment development, inspection, codes and specifications was reported by six international industrial leaders. They summarized the major achievements in underwater technology and emphasized that the technology has matured substantially in the past decade. Examples of successful application of underwater welding repair technology has also been illustrated.

Small group workshops promoted open and active discussion of current technological advances and roadblocks to further progress. From the deliberations of these working groups, white papers that clearly established industrial and research needs, guidelines and recommendations for the future development of underwater fabrication were prepared. Specially designed welding consumables for underwater welding can, in most cases, produce welds with excellent microstructure and properties. The introduction of inverter-based power sources capable of weld voltage and current control was extremely useful in improving the underwater welding processes. Significant amount of effort has been expended in automation and robotic welding, particularly in deep water applications. Current standards on underwater welding/inspection were reviewed by two work groups.

It is highly encouraging to notice that much progress has been achieved in underwater welding during the past nine years. It is also satisfying to know that several of the barriers discussed in the previous workshop had been overcome. However, for full implementation of the underwater technology, more basic and applied research needs to be done. These recommendations are listed in detail in the following chapters of this proceedings.

Several recommendations, however, received the highest priorities in terms of research and development needs and are listed in the following. 1) Recommendations from the Standards Workgroups heightened the need for an improved qualification approach by third-party certification of wet welders and by training and experience as bases for all certification. The development of a comprehensive guide to organize, mobilize and carry out repairs to structures is also recommended. 2) For structural steels with carbon equivalent less than 0.40 wt.pct., Type A and Type B+ welds should be targeted for depths less than 100 ft. and between 100 and 200 ft., respectively. 3) For steels of greater carbon equivalent, there is a need for more detailed investigations with respect to porosity, inclusions, fissuring, alloying element segregation, and hydrogen control in the weld metal. To minimize cracking, fundamental work on diffusible hydrogen modeling should be carried out to determine methods for effective reduction of local hydrogen in crack critical areas. 4) A more longer term approach should be taken to address underwater welding in greater depths. It is the recommendation of the Workgroups that a depth greater than 200 m for shielded metal arc welding should be targeted. Similarly, depths greater than 500 m should be targeted for gas tungsten arc welding, gas metal arc welding, and plasma arc welding. 5) For greater depths, the development of accessories and equipment to support the diverless/robotic welding/inspection processes in eminent. 6) Flux cored arc welding appears to have greater potentials in underwater wet welding and should be further developed using a systems approach.

Finally, the Workshop strongly supported the premise of holding another underwater welding workshop in three to four years.

Research & Development Needs in Underwater Welding/Inspection

PRIORITIZED LIST OF RESEARCH AND DEVELOPMENT NEEDS IN UNDERWATER WELDING

Concerning future development, it was recognized that if the aim is to develop suitable and acceptable solutions for underwater welding in a predictable future, a number of preliminary conditions must be fulfilled.

1. The need to depart from traditional approaches and to "break circle".
2. The need of coordination and direction in the investigation and development of process, consumables, and techniques for underwater welding.
3. The need to recognize that consumables most probably will have to be differentiated according to depth, possibly according to root, fill and/or capping functions.
4. In view of the highly challenging problems that are faced, all possible, even uncommon, designs and incident technologies at hand should be integrated in the development process.
5. In view of the multiplicity of factors involved in the design/formulations, development and evaluation processes, only a comprehensive, multi-disciplinary and systematic, scientifically-oriented approach is likely to lead to real significant progress.

A suggested plan for a more systematic course of development would be to categorize and coordinate the areas of development to provide a more efficient utilization of development resources. A development program must include the following interrelated categories:

1. Conduct a comprehensive review and critique of welding processes and technologies to fully investigate their potential for underwater use.
2. Select the most promising processes for further investigation and development.
3. Demonstrate and provide proof of concept for the selected processes based on:
    a. Weld quality: soundness of weld and HAZ, microstructure, repeatability, and inspectability.

b. Structural performance of welds: create a data base of static strength, fracture strength, fatigue strength, and corrosion resistance.

c. Evaluation of processes from the standpoint of operation in a wet and/or dry environment.

d. Identification of specific areas needing further development and the potential success of the process for underwater application.

4. Educate and expand communication of the underwater welding community on the developing technologies and applications through workshops, seminars and conferences. Promote free exchange of successfull development in underwater wet welding.

5. Develop recommended procedures and specifications based on data obtained through use and qualification of selected processes, technical development, experience of users and operators, and input from regulating bodies.

6. Identify sources of development funding that could include fabricators, regulators, oil companies, equipment producers, federal agencies and international sources.

More specifically, the Working Groups have identified and prioritized the following needs to further underwater welding and its applications in structural marine fabrication.

Recommendation: Consensus Issues

1. Third Party Certification for Wet Welders: Under current certification schemes, the contractor is responsible to certify welders. Entrance into the market of companies with more expertise in diving than in wet underwater welding has led to concern that welder certification may not have been correctly carried out, and that as a result, the overall quality of the industry may be compromised. It is recommended that a third-party certification scheme be implemented by the industry.

2. Supplementary Evidence of Training and Experience: Underwater welding codes and standards should be modified to include training and experience as a basis for certification in addition to the typical performance testing. Adequate training and experience are essential to the capability to consistently perform wet welding with quality results. The means as to how this is achieved is left to the code-making organizations, however, a specifically detailed and tightly structured scheme is not recommended to be included in a code.

3. Prequalification to Similar Surface Welding: The codes do not require prequalification, however, in many cases underwater welding is similar to surface welding. It is recommended that code-making organizations consider prequalification for underwater welding that is similar to surface welding, such as dry hyperbaric.

4. Consider Effects of Restraint: Many codes do not take into account that the effects of welding restrain t can be greater under production wet welding conditions as compared with the conditions j[used for welder qualification. This is due in part to different cooling rates in production welds that are permitted by the

code qualification thickness ranges, and in part by the greater structural restrain inherent to a repair situation that cannot be represented by welding a test plate. It is recommended that code-making organizations consider the aspects of restraint.

5. Maintain Separate Standards for Welding, Diving, and Nondestructive Testing: The concept of a unified standard was not supported due in part to the distinct expertise for the various disciplines and in part to the existence of separate organizations which presently maintain the standards. It is suggested, however, that the separate groups maintain a close liaison.

6. Incorporate wet welding into design standards. There is currently no accepted industry design standards. By developing such a standard, benefits would be seen in the areas of fabrication and installation of marine structures. The incorporation of underwater wet welding in design standards would facilitate subsequent repair of those structures.

7. Develop Guidelines for Damage Inspection and Repair: Although strictly not within the mandate of the work group, this item was identified as one where the industry is in need of improvement. It is recommended to various code-making organizations to consider the development of a comprehensive document that can be used to organize, mobilize, and carry out repairs to structures; with emphasis on pre-inspection, assessment, standard solutions, and follow-up.

8. Safety Issues Should be Addressed: Many industry codes have not addressed safety issues, presumably for reason of potential liability. The work group recommends that a means to accommodate significant safety issues be considered. Simple reference to safety documents is not considered acceptable, in that these

documents can be lacking int he safety issues specific to the activity of underwater welding.

9. More frequent update of the underwater welding/inspection standards with respect to:

    - specific electrode classification for underwater welding
    - new welding and inpsections process introduced
    - environmental impact of underwater technology
    - evaluation and comparison of test weld and field weld data

10. More thorough documentation and analysis (understanding) of existing data on current and past underwater welding applications, in particular, joint performance and mechanical properties.

    - Compile data on the usage of underwater welding repair in recent major repair projects - These projects will be analyzed, and the applications (cause of damage, intent of repair, other repair options considered, design criteria used, etc.) documentedy.
    - Analyze existing fracture test data on weld heat affected zone with static and dynamic loading conditions - There are specimens generated in the past by the underwater welding industry that may be available for this research.
    - Investigate underwater repair as a part of platform salvage operations - This program will gather data on aged repairs performed on platforms being salvaged. Former repair welds will be analyzed using destructive and non-destructive techniques to determine characteristics and integrity of the weld over time. Extremely valuable data will be collected to enrich any exisitng database of underwater welding for future applications.
    - Fatigue analysis of underwater wet wets - To establish a fatigue test and evaluate one of more underwater weld repair mockups.

Recommendations: Materials Issues

1. For steels with carbon equivalent less than 0.40 wt. pct.:
   a. For depths less than 100 ft. Type A welds (instead of the currently accepted Type B welds), by reducing porosity, by improving ductility and impact toughness, should be targeted.
   b. For depths between 100 and 200 ft., Type B+ welds (instead of the currently accepted Type B welds), by reducing porosity, by improving ductility and impact toughness, should be targeted.
   c. For depths between 200 and 325 ft., Type B welds (instead of the currently accepted Type B- welds), by reducing porosity, by improving ductility and impact toughness, should be targeted.
2. For steels with carbon equivalent between 0.40 and 0.46 wt. pct.:
   a. There is a need for more detailed investigation with respect to porosity, inclusions, fissuring, alloying element segregation, and hydrogen control in the weld metal.
3. The use of electrodes with high oxygen potential has shown promising results in underwater wet welding and should be further investigated for optimal effect in balancing porosity with inclusions and hydrogen control.
4. Consumables should be developed for welding the new TMCP steel, in particular, to produce weld metals with toughness that matches those of the base metals.
5. Priority in further consumable development should be focused on C-Mn-Si and C-Mn-Si (Low Alloy) systems with microalloying elements such as titanium and boron.
6. The rutile-cellulosic (E6013 Type) and rutile (E7014 Type) slags are capable of delivering quality underwater wet welds. Further improvements of these systems, expected to result in high quality consumables which will achieve the weld quality

proposed earlier, should be targeted. Flexibility in design could be achieved by using coated tubular cored electrodes.

7. For consistent demonstration of wet welding techniques that are effective in avoiding cracks, modeling of hydrogen diffusion profiles by FEM calculation including temperature profiles of actual joint configurations should be carried out indicating required measures for efficient reduction of local hydrogen in crack critical areas with respect to microstructure and stress/strain.

Recommendations: Welding Processes Issues

1. SMAW: Extend applicability of the SMAW process to depths greater than 200 m, especially increase knowledge on the effects of pressure on process behavior.

2. GTAW: Further R&D work required on process performance beyond 500 m, particularly considering topics on arc stability, electrode performance, arc ignition procedures, evaluation of new shielding gas mixture (Ar based), evaluation of process performance considering cold wire addition (arc stability, process efficiency, and productivity).

3. GMAW: Extend applications for depths beyond 500 m. This research needs to include an improvement of process behavior (arc stability and metal transfer) considering: shielding gas composition and out-of-position welding, development of process control strategies for the short circuit transfer modes, development of root pass procedures (based on narrow gap joint configuration), and evaluation of the behavior of metal cored wires for this application (process and weld metal properties).

4. Plasma Arc Welding: Extend the application for multipass joints beyond 500 m.

5. The use of FCAW has great potentials in underwater wet welding. Developmental work in the design of consumables, wire feeder and power design, using a systems approach, is strongly recommended.

6. Equipment: (a) Improvement of torch design (GTAW, GMAW, and Plasma) considering diverless applications. (b) Development of sensors which could lead

to the reliable diverless deposition of root runs, such as: seam tracking, root run penetration control (i.e. front face penetration control, weld pool oscillation frequency, etc.), and de-mangnetization.

7. Diverless Repair Technology: Fitness for purpose analysis of a diverless sleeve repair.

8. For the extension of wet welding into deeper water and more challenging environments, a consistent documentation of recently performed wet welds and their service performance should be carried out. Such performance should be documented by: type of electrodes, layer technique, joint type including thickness, position, heat treatment, NDT results, qualification testing, service time, and service load spectra including corrosion.

9. For verification of service behavior of wet welds in more challenging environments and deeper water, backing up fatigue testing in sea water under realistic loading conditions should be performed.

9. For consistent demonstration of effective crack avoiding wet welding techniques, modeling of hydrogen diffusion profiles by FEM calculation including temperature profiles of actual joint configurations shall be carried out indicating required measured for efficient reduction of local hydrogen in crack critical areas with respect to microstructure and stress/strain.

10. As a consequence of reduced physical abilities of divers below 500 msw, the verification of quality hyperbaric welding joints beyond this depth may be achieved by either automated NDT systems or suitable online process control. R&D work

on both methods are recommended to be carried out. The following processes may be suited for online process control: FCAW, GMAW, GTAW, PAW, friction and flash butt welding.

INTRODUCTION

Much progress has been made in the engineering and practice of underwater welding since the last international workshop in November, 1985, at the Colorado School or Mines. The 1985 workshop, sponsored by the United States Department of Interior - Minerals Management Service (MMS), identified problems associated with design, processes, metallurgy, and inspection. The workshop also prioritized problems and identified opportunities for research and development. The 1985 workshop report has been most valuable to industry, certifying bodies, and government in their efforts to advance underwater welding.

In spite of many successful applications, underwater welding requires further research, development and education to achieve its full potential. Complete implementation of underwater welding will require an increased confidence level from design engineers and corporate leaders, advancements in technology to reduce cost and increase weld integrity, and more complete international standards and certification programs. For these reasons, an organizing committee consisting of recognized experts from around the world was established in late 1993 to put together a program that will:

1. define the status of the engineering and practice for underwater welding and inspection,
2. identify technical and non technical problems hindering the full utilization of underwater fabrication technology,
3. identify new and advanced technology with potential in underwater welding,
4. promote the use of underwater welding incorporating the concept of fitness-for-service,
5. produce an archivable record that thoroughly describes current practice in underwater welding, and opportunities for utilizing underwater technology, and
6. promote collaboration amongst the practitioners of underwater welding.

WORKSHOP OVERVIEW

The format of the 1995 Workshop in New Orleans was unique that it carefully balanced the 2-1/2 day workshop with presentations on current status of engineering practice in underwater welding and the working group sessions in which discussions on research and development needs were held. A total of six presentations were delivered which covered the areas of:

1. State-of-the-art and practice of underwater wet welding,
2. State-of-the-art and practice of underwater hyperbaric welding,
3. Technology transfer,
4. Fitness-for-service design and application for underwater wet welds,
5. State-of-the-art and practice of underwater inspection, and
6. Case studies of success in underwater welding repair (economics and design).

The manuscripts of these presentations are included in this volume.

1. Further developments on standards, specifications and codes (welding and inspection),
2. Welding consumables and weldability,
3. Consensus diver/welder performance testing and qualification,
4. Processes (equipment, robotics, hyperbaric and mechanization),
5. Deep water applications, and
6. Advanced technology and challenges.

Each working group started with the presentation of a white paper which identified the research and development needs, opportunities and important ongoing projects, and barriers to the progress and application of underwater welding. The position white papers were delivered to the participants prior to the session. During the working group period, the participants were encouraged to visit more than one session to maximize their contributions to the different aspects of underwater welding. For the final session of the working groups, the participants were charged to prepare lists of prioritized action items for the final workshop assembly.

The atmosphere of the workshop was extremely positive and upbeat. All participants felt that the technology is undergoing significant progress and it is not too far reached for the qualification of Class A welds even for wet welding down to 200 ft. As to hyperbaric welding, equipment and processes are progressing rapidly that many prototypes are already being implemented. In terms of fundamental research, the availability of good consumables is still the major problem. More fundamental studies coupled with experimentation are needed to understand and control the weld cracking and porosity problems. Process and weld modeling are progressing but in small increments. Several new processes have been introduced and may improve significantly the quality of underwater welding.

ACKNOWLEDGMENT

The organizing committee would like to extend their most sincere gratitude to the Department of Interior - Minerals Management Service (MMS) and American Bureau of Shipping for sponsoring this event. Their support went well beyond the financial aspect of the workshop, their staff support was greatly appreciated. The major industrial sponsors are also acknowledged for contributions which made this event possible. The industrial participants with booth exhibitions are greatly appreciated for their effort in bringing their information to the workshop. During the Workshop, two participants, Dr. Jesse Grantham and Mr. Bob Franco, were requested to visit as many workgroup sessions as possible and prepare a participant's critique of the Workshop. Their efforts are gratefully acknowledged. Finally, the organizing committee congratulates each of the participants for their active participation in the working group sessions with questions, comments, and suggestions. As to the request for holding the next underwater welding workshop within the next five years, it will be made known to the concerning parties.

Supporting Remarks

SUPPORTING REMARK FROM
A U.S. REGULATORY AGENCY

Dr. Chris Oynes
Department of Interior - Minerals Management Service

Good morning, ladies and gentlemen, and welcome to this International Workshop on Underwater Welding of Marine Structures. As you can see from your brochure, this workshop is being sponsored by several notable organizations and companies, one of which is the Minerals Management Service.

We are the regulatory agency responsible for overseeing oil, gas, and sulfur operations on the Outer Continental Shelf (OCS) of the United States, and my remarks this morning will therefore address MMS interests in this subject. The regulatory document which enumerates our exploration and production requirements is the Code of Federal Regulations, 30 CFR 250. For the most part, MMS requirements are performance based and are intended to assure, to the maximum extent possible, that offshore operations are conducted in a manner which is both safe and minimizes the potential for pollution. Therefore, under Subpart I and J of the regulations, platforms, structures, and pipelines are required to be properly maintained in order to meet that objective. Such maintenance often requires the underwater repair of structural damage which may result from any of a number of causes. Metal fatigue, corrosion, dropped objects, boat/rig contact, or environmental overload represent the main culprits causing underwater damage, and the longer a structure or pipeline remains in place, the greater its chances of experiencing one or more of those problems. It is noteworthy that some of the older existing OCS structures date back to the late 1940's. Several hundreds of those structures are more than 20 years old, a figure which has often been used to derive the "design life' of most of them.

With the incorporation of periodic underwater structural inspection requirements into MMS regulations in 1988, the discovery and reporting of underwater damage appears to have increased substantially. Further, with the advent of new exploration and production technologies, operators are finding it economically advantageous to extend the useful life of both platforms and pipelines. When combined, these two facts tend to indicate that operators will be dedicating significant efforts and funds to underwater repairs in future years.

Although repairs to underwater structures and pipelines can be performed using a number of acceptable methods (e.g., mechanical clamps, grouting, welding), underwater welding seems to be one of the most popular means of repairing damaged steel members. However, given the cost and technical limitations which presently exist regarding underwater welding, technological advances are needed for it to be used extensively and effectively in the future. To this end, the MMS provided funding for this workshop and is presently funding other research which we hope will "push the envelope" that presently exists for underwater welding technology. It is our belief that the lives of existing oil and gas fields can be safely extended, in part by the development of acceptable, effective, and cost effective methods of maintaining the underwater portions of platforms and pipelines.

It is noteworthy that the MMS supports an active research program which seeks to enhance an understanding of the engineering constraints for offshore operations, especially as they relate to the prevention of pollution, integrity of structures and pipelines, and technologies necessary to clean up any oil spills which may occur. Information derived from such research is integrated into offshore operations and is used in making regulatory decisions pertaining to the issuing of permits and the review and approval/disapproval of lessee submitted proposals. The research program is basically a contract research program, one wherein research is performed not by MMS, but by academic institutions, private industry and government laboratories. Studies are performed in cooperation with the offshore industry and/or with federal, state, and foreign governments. Such an approach provides for important dialogue and provides the opportunity for both industry and government to work together in assessing technologies and future developments beneficial to all.

For those of you that are interested, future MMS workshops include:

- Damage to Underwater Pipelines - February 22-24, 1995 in New Orleans, Louisiana.
- Sea Ice Mechanics and Ice Modeling Workshop - April, 1995, in Anchorage, Alaska.

Additionally, the MMS is helping in the organization effort of the "Second International Workshop on Wind and Earthquake Engineering for Offshore and Coastal Facilities" to be held in Berkeley, California from January 17-19, 1995.

I trust you will find the next three days interesting and informative, and encourage you all to actively participate in one of the various working groups.

SUPPORTING REMARKS FROM A U.S. CERTIFICATION AGENCY

Dr. Jack S. Spencer
American Bureau of Shipping

I would like to thank Dr. Olson and the Colorado School of Mines for inviting the American Bureau of Shipping to participate in this Underwater Welding of Marine Structures Workshop, and for inviting me to speak before this distinguished group. We anticipate lively discussions and a stimulating interchange of opinion over the next several days, and look forward to the conclusions and direction that the Workshop will provide in the area of underwater welding. These will undoubtedly be of great value to the marine industry and to other industries as well.

As you are probably aware, the American Bureau of Shipping is the primary American classification society and has as its mission promoting the security of life, and property at sea, and protection of the natural environment. ABS does this by setting standards for design, construction and operation, principally for surface vessels but for many other kinds of marine structures and systems as well. These standards also include repair to marine structures, and so they have an impact on the topics under discussion at this Workshop.

Traditionally, sea-going steel vessels are repaired in port and where necessary in dry dock. Repairs are intended to return the vessel to a condition of design or under certain circumstances to a level of repair that is considered satisfactory for continued service and safety, keeping in mind the current age and anticipated longevity of the vessel. This approach has been fostered by the various public and private agencies entrusted with marine safety, such as the National and International Administrations, the Classification Societies, and the Underwriters.

On occasion vessels are so badly damaged that temporary repairs must be carried out so safe passage to the repair facility can be made. These repairs are recognized as not being permanent nor returning the vessel to the design condition, but as only putting the vessel in a condition whereby limited operation under reduced serivce conditions is possible. Underwater wet welding has been applied under such circumstances, although the properties of the wet weld repairs are recognized as being inferior to that of the original construction welds.

From this very conservative approach has evolved a more flexible and economical system where repairs can be completed in situ - on the vessel wherever it may be. The principal factor in this approach has been the development of underwater welding as a useful tool. ABS has accepted permanent repairs to vessels by means of dry underwater welding and in limited cases by wet underwater welding. The cases of wet underwater welding take into account the structural criticality of the repair and also possible failure scenarios. Recent examples have been the repair to secondary structure related to a propulsion system, repair to vessel hulls at locations protected by water-tight bulkheads, and repair to doublers where the repair welds are segregated from the shell structure. This is the state of underwater welding presently applied to commercial surface ships as seen through the certification agency eyes of the American Bureau of Shipping.

To better convey our approach to underwater welding to the industry, ABS is currently developing a formal guide for underwater welding of ship structures that will cover dry welding and wet welding, and it will address processes such as shielded metal arc welding, flux-cored arc welding, gas metal arc and gas tungsten arc welding. The guide will restrict the application of wet welds until such times that Type A quality can be reliably and reproducibly demonstrated.

We appreciate that much research has been done and continues to be done in the area of underwater welding; ABS has been involved in some of the research. A recently completed Ship Structure Committee report, SSC-*370 Underwater Repair Procedures For Ship Hulls*, has shown that the properties developed from wet underwater welding are not detrimental for welds at certain locations in the structure where lower ductility can be tolerated. Copies of this report are available at the ABS exhibit on the second floor. Regarding the properties of welds deposited by wet underwater welding, there will be workshops this week on welding consumables and there are theme papers on wet underwater welding and fitness-for0service design.

The American Bureau of Shipping has also worked with the E.O. Paton Institute regarding wet flux-cored welding. We presently have a Memorandum of Understanding with the Paton Institute for cooperation in technology, business, and research & development including technologies such as underwater welding. This transfer of technology between companies, countries and even across former political barriers will in the long run benefit all who participate. As suggested by the attendance here, there are very many groups, both national and international, participating in technology transfer and striving for the advancement of underwater welding technology. We are fortunate to be here participating at this International Workshop to help exchange ideas, information and data, and to help focus and prioritize the needs for future research.

ABS has a keen interest in underwater welding, and desires that the technology continue to grow and serve a greater list of applications, structures and industries. We believe that this Workshop will document the current state of the art in underwater welding and will provide appropriate direction for further research and development. The research areas of primary interest to ABS at the present time are as follows:

- First, to improve the quality of wet welding of marine structural steels to Type A: This will enable permanent weld repair to be made to ship structures in the afloat condition and without the need of expensive drydocking. The steels of concern are mild steels of about 34 ksi yield strength and high strength steels of up to about 56 ksi yield strength.

- Second, to improve the reproducibility of weld quality:
  This will ensure that the quality of welds demonstrated in the welding qualification testing will be that obtained when welding on-site is performed.

Although the majority of ABS's business is concerned with classification of surface vessels, structural and welding issues on other types of marine structures are also of interest. These include fixed offshore platforms, undersea pipelines and floating offshore exploration and production units. Underwater welding is an important consideration for repair of those structures, and ABS has been involved with successful repairs generally carried out by dry welding methods. Thus, we look forward to the planned discussions of underwater hyperbaric welding, case studies of repair to fixed offshore platforms, and deep water applications. We are particularly interested in novel repair approaches that overcome the problems inherent to wet welding, such as special joint design.

Effective underwater inspection is equally as important as quality underwater welding to the overall success of the repair operation. We have seen a strong interest develop in eddy current methods as proposed replacements or supplements to the more traditional magnetic particle methods of inspection. ABS maintains a program for the certification of underwater inspection companies. We note that this week there will be a workshop on advanced technology and inspection and a paper summarizing the state-of-the-art and practice of underwater inspection.

In addition to the technology and the specific technical issues of underwater welding, the American Bureau of Shipping is also concerned with the certification of welding operations, welding procedures, welder performance, and fitness-for-purpose of subsequent welding repairs. Appropriate standards, specifications and codes are the bases that support this certification activity. ABS is very interested in the proper application of standards, as well as with improving them and introducing new standards that incorporate new technology. The standards applied to underwater welding should be technically correct and capable of predicting worksite usability, yet not too restrictive on industry.

Further, ABS supports the development of consensus standards to minimize unnecessary expenses associated with redundant qualification. We look forward to the workshops dealing with standards, specifications and codes for underwater welding and inspection, and to the workshop on diver-welder qualification. The paper on certification of underwater welding operations is also timely.

A review of the topics chosen for the workshop activity and the subjects for the theme papers shows that this Workshop will address the major challenge areas in underwater welding, and also areas where successful results have been achieved that represent the state-of-the-art and practice in underwater welding.

The American Bureau of Shipping fully supports the ongoing efforts in underwater welding and encourages everyone here to actively participate, so that this Workshop will develop useful guidance for the direction of future research. The commercial marine sector will benefit greatly with the advancement of underwater welding technology. It has been a pleasure to speak before you this morning to share our enthusiasm for this Workshop, and to briefly describe ABS's interest, experience and desired improvements in underwater welding.

Thank you very much.

Supporting Remarks from
IIW Select Committee on Underwater Welding

Professor Hans Hoffmeister
Universität der Bundeswehr, Hamburg, Germany

Remembering my first riverboat dinner in New Orleans in December 1950, as an 18 year old boy, it seemed to me as if I had to plunge into dark unknown, maybe also dangerous areas of social life. As it turned out, however, it really did not matter whether I had any knowledge of typical southern food, of the art of throwing coins into the waters of the Mississipi to let kids dive after it or even of the effect of the very first glasses of Jack Daniels on my mental abilities. The tolerated range of errors without punishment was rather wide and there were no specific capabilities required for surviving this very remarkable event.

The situation is of course different if one gets involved in getting hold of offshore oil and gas resources at water depths of down to 1000 m. In this case the mobilization of available cababilities is mandatory. In particular, if it comes to welding of marine structures including pipelines in wet or dry hyperbaric challenging environments, one should be in the position to put the right questions and also, answer them properly.

Such questions could be: **Do we know what we are doing in underwater welding?**
Do we know the consequences of what we are doing?

More in detail, such questions could be adressed to the working areas being identified by the first Underwater Welding Workshop in Golden, Nov. 1985, as for instance:

Mechanized deep sea welding systems
Arc stability in TIG hyperbaric welding
Development of consumables for TIG and MIG hyperbaric welding
Hydrogen cracking tests for hyperbaric conditions
Development of hyperbaric Plasma Welding

Since then, considerable progress has been achieved as being demonstrated by a few following examples:

For permanent availability of repair resources,the hyperbaric "PRS" - pipeline repair system has been established by STATOIL and Norsk Hydro A/S which is also used for numerous tie-in procedures in the North Sea environment.Similar installations have been developed by Comex-Seaway.

For economical and technical performance of the PRS system, basic investigations were carried with respect to tungsten electrode wear properties, arc deflection behavior and root penetration in hyperbaric TIG welds.

Dry hyperbaric GMAW investigations and developments have been focussed on controlled, spatter free droplet transfer at pressure together with gas -metal interactions and pick up of nitrogen and hydrogen. In addition,hydrogen assisted cracking at increasing pressure has been shown to decrease at constant partial hydrogen pressures due to less pick up of hydrogen.

This leads to the questions which are presently raised with respect to the capabilities of wet underwater welding and which might occupy the minds of a majority of the workshop attendants.

The lesson being learned so far, is that according to the above rather simple questions,

- **the actual service conditions of marine structures with regard to mechanical and corrosion impacts,**
- **the welding processes with regard to their mechanism and parameters, depending on pressure and water,**
- **the effect of welding on weld joint properties with regard to required service performance of the structures.**

Quantification means of course, documentation of what happens and why it happens. Consequently, a lot of paper work or software is to be processed for consistent conclusions and applications. It means also in particular, to establish and apply appropriate models of mechanisms in question for prediction and maybe online control.

Attention is also drawn to the opportunity of reduction of amount of required NDT, for instance, by online videorecords of complete process sequences including droplet transfer, arc stability, penetration and melt behavior with respect to lack of fusion, porosity and other defects. A typical example of latest developments is represented by hyperbaric Plasma Arc Welding at 21 bar of a duplex stainless steel being penetration controlled by online video. It should be stressed,that at increasing depths, manual NDT is increasingly difficult and might be replaced by such procedures in the future.

It is with this background that the Select Committee Underwater Welding of the IIW recently established standard guidelines for specifications for underwater fusion welding. These guidelines (IIW DOC SCUW 124-90) are presently in the process of being converted to an ISO standard. They shall provide an accepted framework for establishment of underwater welding specifications, in particular, for mechanized controlled procedures.

In any case, the purpose of a specification is to provide the credability being required for the acceptance and the efficiency of the work being done and for the safety of the involved people. It should be kept in mind that any R&D work finally serves to the establishment of such specifications and, therefore, should provide the quantitative background for it.

As I put it in the beginning, the key to it might be to ask the right questions and find the right answers.

With this background I should like to thank for the invitation to take part in the workshop and to contribute to it. I wish you all a successful performance.

Keynote Addresses

KEYNOTE ADDRESS FROM
A U.S. OFFSHORE INDUSTRY

Sheldon Fortenberry
Chevron Petroleum Technology Company

First I would like to thank the U.S. Minerals Management Service (MMS) and the Colorado School of Mines for their efforts in organizing and sponsoring this very important international workshop on the Applications of Underwater Welding to Marine Structures.

As many of you are aware, the last international workshop on underwater welding was held at the Colorado School of Mines in 1985. This workshop was very successful in prioritizing the many problems associated with underwater welding and identifying opportunities for research and development. This year's workshop has the same goals, and I am sure it will be as successful.

The U.S. Petroleum industry has undergone dramatic changes since those boom days of the 70's and early 80's. The worldwide drilling boom led to a huge glut in oil. By the mid 1980s, prices collapsed, U.S. production declined and our industry seemed to fall off a cliff. For a while, it seemed our industry was an endangered species similar to the Ridley Turtle.

According to most industry estimates, existing oil and gas production will trend dramatically downward within the next ten years. But I think all of us -- the entire petroleum industry -- demonstrated a diehard ability to re-engineer ourselves. Some of the keys to staying competitive have been reducing operating costs, a commitment to safe operations, utilizing key technologies, and an emphasis on continuous quality improvements in all phases of the business. We have managed to slow production declines, and production actually rose 4 percent after the 1990 Persian Gulf crisis.

The U.S. Oil industry has made significant progress in all of the above areas; however, incremental reductions from here on will be increasingly difficult. I believe that one area that industry, academia, and government must continue to work together is in underwater welding technology.

Activity related to wet welding increased significantly in the 60's and 70's to meet the demands of the offshore industry. Most of this development has been by the people who performed the actual welding underwater. This practical approach has been very successful in the past. However, I feel that we need to have some involvement by industry, academia and government so that further breakthroughs can be realized.

The industry has had many successes with underwater welding over the years. I am not aware of any properly designed wet welding repair made in the Gulf of Mexico (GOM) that has not been successful. Chevron alone has made over 250 repairs on over 60 platforms in the GOM utilizing underwater welding. The location of these repairs ranged from the splash zone to 250 feet below the surface. The great majority of these repairs utilized wet welding which has saved Chevron considerable dollars.

In the summer of 1992, Hurricane Andrew with sustained winds of 140 miles per hour, tracked through the South Timbalier, Ship Shoal, and Eugene Island Areas of the GOM and caused considerable damage.

According to MMS estimates, approximately 2,000 out of 3,900 oil and gas facilities in Outer Shelf Shelf (OSC) waters were located within 50 miles to either side of the hurricane path. Thirty-six major platforms and 165 small satellites (mostly caissons and single well tripods) of the 2000 platforms suffered significant damage. A total of 10 major platforms and 25 satellites and caissons were completely toppled. The other structures suffered combinations of topside and underwater damage and many caissons were found leaning.

Chevron U.S.A. is the largest operator in the GOM and is responsible for inspecting and maintaining over 1000 offshore platforms. Approximately half (500) of Chevron's structures were exposed to severe environmental loads by the Hurricane. As a result, Chevron lost three platforms and two caissons. Later, after the post-Hurricane inspection, three additional platforms were condemned, and nine structures required repair for continued safe use.

One very significant point is that approximately 30 of Chevron's platforms previously repaired by wet welding were exposed to Hurricane Andrew. There were no failures of the underwater welds.

Chevron utilized wet welding to repair the nine structures damaged by Hurricane Andrew. These nine platforms required repairs at 34 individual weld locations. Repairs were made on damaged members located from the water line down to 160 feet. The repairs cost nearly $1,000,000 and took 61 days to complete.

The ability to economically repair these platforms made the difference between continuing production or abandonment. We found that the cost savings using wet welding instead of dry hyperbaric or one atmosphere system has been significant. Wet welding allowed for greater flexibility, was much easier to mobilize and took less time for the repairs. This is critical when down time or possible damage to the environment is a factor.

As mentioned earlier, approximately 3900 OCS platforms existed in the GOM during Hurricane Andrew. Nearly half of these platforms were designed prior to 1977 and do not meet the current API 2A design criteria required for new platforms. The proposed draft of API 2A Section 17 allows for these older existing structures to remain in service; however, some of these structures may require strengthening or repair. One of our challenges is to economically and safely maintain these platforms for their intended use. Furthering the technology of underwater welding is critical as we extend the life of these older structures. This is particularly true in shallow water where the majority of structures exist.

One of the most significant developments in the past 20 years has been the publication of AWS D3.6 Specification for Underwater Welding. This specification, first publication in 1983, allows a client to safely specify and obtain underwater wet welds that are predictable and verifiable for pipeline and critical platform members. This specification has a positive effect not only on companies that perform underwater welding, but also for the oil companies that rely on this technology for consistency of design.

Significant improvement has been made in understanding the factors affecting the metallurgy and control of underwater welds and their heat affected zones. The most significant impact has been on better electrode coatings, improved welding techniques such as the temper bead and half bead techniques, and understanding the effects of greater water depth.

A new wet welding electrode has recently been developed by a Joint Industry Project (JIP) that significantly improves the quality of wet welds. This JIP was originally proposed by Global Divers and is being carried out in conjunction with the Colorado School of Mines. The initial electrode research and development work has been done at the shallower water depths (less than 33'). Results to date have been very encouraging and have shown that we can produce wet welds with significantly less porosity that meet the more stringent radiographic quality requirements for AWS D3.6 Class A welds. In addition, these welds have improved notch toughness and greater elongation.

Another important aspect of this JIP has been the joint sponsorship by industry, academia, and government. I feel this collaboration is critical in solving the complex problems associated with wet welding. Combining the theoretical and practical approach to research is a critical step needed to advance underwater welding. This approach will significantly improve electrodes and welding techniques required to produce wet welds.

Working together we can produce welds that have reduced porosity, better mechanical properties and are more resistant to hydrogen cracking in both the weld metal and base metal.

So where does the U.S. Petroleum industry stand today? We have overcome more than 100 years of ups and downs, political barriers and doomsday forecasts. We are also coming off one of our most discouraging decades ever. The world still has plenty of oil and natural gas. No one has found a cost-competitive alternative, and our products and technology will continue to improve. Many areas with promising prospects for oil and gas are "off-limits". However there are still plenty of opportunities such as deepwater frontiers and subsalt plays.

Underscoring all of these new opportunities is the bedrock of our industry -- breakthrough technology. It not only helps to push beyond the barriers into new frontiers, but it helps resuscitate older fields. One of the best examples of this is Chevron's 45 year old Bay Marchand Field -- one of the most prolific offshore fields in the U.S. New technology such as 3D seismic and horizontal drilling techniques have extended the life of Bay Marchand well into the future. Maintaining these very old platforms by utilizing new underwater welding technology will also help extend their productive life. This technology may also be used to increase the size or load carrying capacity of an existing platform.

Current oil industry economics make continual cost and efficiency gains a necessity. Sustainable cost and efficiency gains will come from new or improved applied technology.

Our dilemma is that current oil prices have caused a shrinking of technology budgets in all segments of our industry. With the globalization of the oil and gas industry, we need to join forces to share and focus on technology improvements.

An example of this is the current efforts by the International Standard Organization (ISO) to develop offshore standards with true world wide applicability. The AWS D3.6-93 Specification was submitted to ISO as an international standard under the fast track system. However, this process has been extremely slow. There are considerable economic advantages to both the industry and individual companies. A single document will bring consistency to the design process. Reduction in errors and oversights translates into safer and more economic facilities. This will quickly allow updating of standards by incorporating the research and development efforts of all countries.

I am convinced that working together we can advance underwater welding technology and significantly reduce the cost associated with maintenance and repair of marine structures worldwide.

One of our challenges is to continually improve the underwater technology (i.e., better understand the relationship between ductility and toughness and elevate the quality and reliability of welding processes) in conventional water depths so that industry can economically extend the life of many older marine structures. As the industry moves farther offshore, our challenge is advance welding processes that have little sensitivity to depth and we must consider mechanization and automating the welding operation. We will need a cooperative effort between operators, contractors, academia and government representatives working together to successfully accomplish our goals.

Thank you -- and I hope that each of you not only learn but share successes in all aspects of underwater welding during the next few days.

KEYNOTE ADDRESS FROM AN INTERNATIONAL OFFSHORE INDUSTRY

UNDERWATER WELDING AT PETROBRÁS

Carlos Soligo Camerini - PETROBRÁS Research Center
Head of the Materials Technology, Equipments and Corrosion Sector. (M.Sc.)
Valter Rocha dos Santos - PETROBRÁS Research Center
Equipments Engineer. Materials Technology, Equipments and Corrosion Sector. (M.Sc.)

ABSTRACT

Some data about present and future offshore activities of PETROBRÁS indicates a clear trend toward the growth of production in ultra-deep waters and, thus, toward a strong demand for a broad development on underwater technology. Concerning underwater welding some test results on wet welding are discussed and lines of action are suggested to further develop this technique aiming its confirmation as a reliable method of structural repairs. The growth of the pipeline network in depths inaccessible to the diver intervention establishes a major challenge, namely the development of fully automated repair systems. Consideration is given to the feasibility of using industrial robots adapted to the hyperbaric environment, furthermore the domain of hyperbaric welding technology in deep waters is presented as the basic stage for developing such systems.

OFFSHORE ACTIVITIES AT PETROBRÁS

PETROBRÁS has been making important oil strikes in waters deeper than 400m. This exploratory success is mainly reflected by the Albacora (1984) and the Marlim (1985) giant fields, and other more recent discoveries, also in the Campos Basin. These fields are located at distances reaching 80 miles offshore, where water depths range from 300 to 2000 meters. The reserves, located in waters between 400 and 1000 m (deep waters) and beyond 1000 m depth (ultra-deep waters), account for 56% of total oil and gas reserves in Brazil (Figure 1). The importance of deep water technology is also stressed by the fact that 66% of the potential oil discoveries in Brazil are related to deep and ultra-deep waters (Figure 2), according to PETROBRÁS experts.

At present the offshore activity already stands for the major part of the Brazilian oil and gas production (Figure 3). The data presented in the Figures 4 and 5 also show a clear trend toward deep waters. About 24% of the crude produced in Brazil comes from wells in waters deeper than 400 meters. Barring any major onshore or shallow-water findings, PETROBRÁS expects this figure to reach 61% by the year 2003. The deepest well in production is located at 1027 m below sea level and forecasts are that during the first decade of the next century depths higher than 1500 m will be reached.

The outlet of the production in the Campos Basin flows through a pipeline network presently estimated at 2500 Km and growing into depths inaccessible to man, despite the present limitations of the deep diving technology. The above data signify an enormous technological challenge requiring the development of new technologies to be applied to a wide range of activities, from the design proper up to the maintenance of the production and transport facilities, which includes diverless underwater interventions.

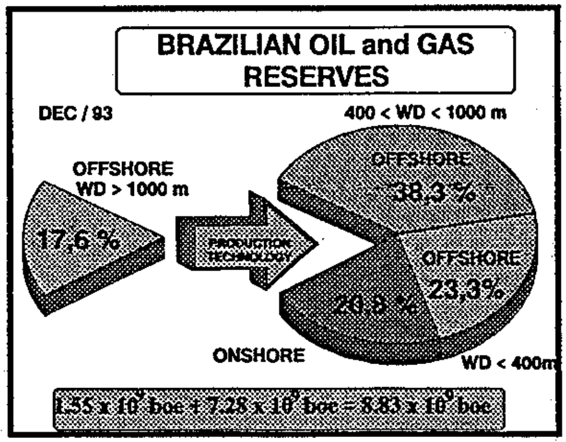

Fig 1: Present brazilian reserves

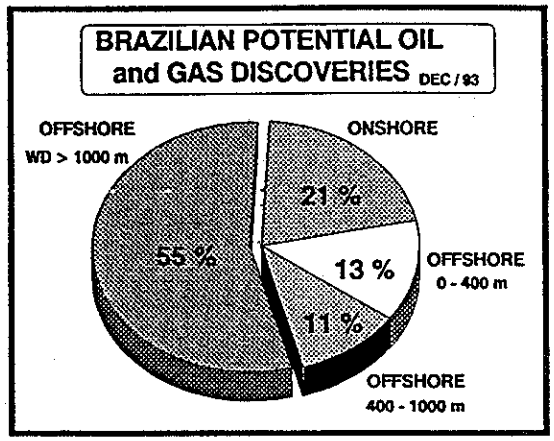

Fig.2: Potential brazilian reserves

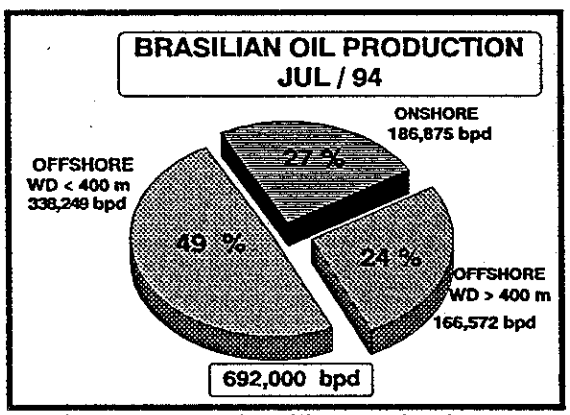

Fig. 3: Present brasilian production

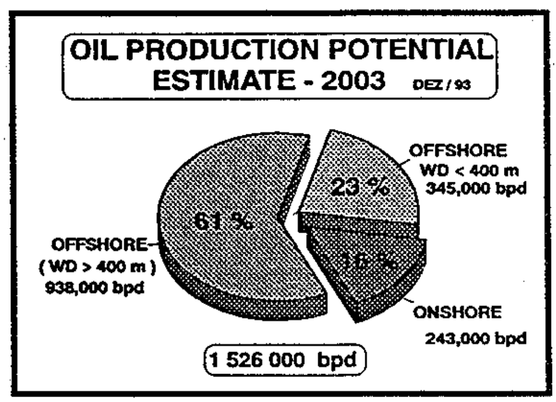

Fig. 4: Potential brasilian production

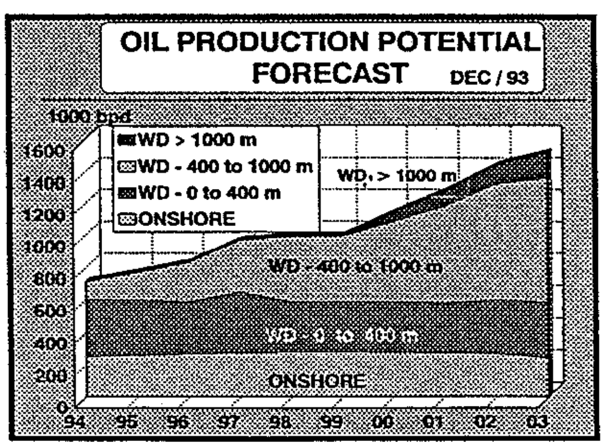

Fig. 5: Brazilian oil production forecast

APPLICATIONS OF UNDERWATER WELDING AT PETROBRÁS

The majority of the damages in the PETROBRÁS offshore facilities has occurred at limited depths allowing interventions by means of air (shallow) diving. In the case of structures, repair methods employed have been wet welding, hyperbaric welding, mechanical reinforcements and grouting. Wet welding has been largely applied in less responsible tasks of the class C, as per AWS D3.6. standard, such as, for instance, the installation of anodes. The utilization of wet welding for structural requirements has been restricted to one single situation: the installation of braces to give support to production risers by means of welding the base-plate of the brace to the waiting plate of the shoulder of a concrete platform. In all other structural applications hyperbaric welding, mechanical reinforcement and grouting were preferred after the study of the most adequate method according to reliability and cost criteria.

In order to reduce lost profits caused by the interruption in the oil or gas production due to damages of submarine pipelines, a contingency plan was implemented in the Campos Basin utilizing mechanical connectors installed by divers as the prefered method.To a lesser extent shallow waters submarine pipelines in smaller fields or terminals have been repaired by means of hyperbarically welded ball joint type connectors

In spite of the large number of platforms in the Campos Basin, commissioned in the seventies, only two repairs were conducted by hyperbaric weldings which involved saturation diving. In both instances the repair consisted of cutting and replacing the damaged stretch of risers at 100 m depth.

In view of the inexistence of proven technologies for the 'in situ" repair of deep water pipelines (beyond 400m) the solution selected in these cases is lifting the ends of the pipeline to the surface, after cutting the damaged section, and the insertion of a flexible line stretch between them. This procedure, however, presents two limitations: the diameter is limited to a maximum of about 16 inches and the pipeline must manain its integrity lest buckling might occur during the lifting.

WET WELDING DEVELOPMENTS

In the course of the last four years PETROBRÁS has been undertaking research on Shielded Metal Arc Welding (SMAW) with the purpose of qualifying wet welding procedures in accordance with the ANSI/AWS D3.6 class B standard. Inasmuch as the great majority of wet welding applications takes place in shallow waters, tests were limited to a maximum depth of 35m. Within the framework of this program it was sought to develop new formulations for the coating of electrodes which, in addition to improved mechanical properties, would be less susceptible to cold cracking. The decision to invest in developing electrodes with lower diffusible hydrogen contents was taken bearing in mind the experience acquired in several previous works that indicated difficulties in utilizing alternatives cold cracking fighting methods, such as the temper bead technique. The main obstacle encountered, in this case, was the difficulty to have constantly trained teams of welders who would be capable of performing at any moment welding jobs within the strict performance standards demanded by this technique. Table 1 lists some properties of the most recents oxydizing electrodes version developed by ESAB-Brazil. Despite of the low depth

(1,5 m) the results are most encouraging, pointing at the possibility of combining good toughness and low diffusible hydrogen levels.

Table I - Wet welding properties

Electrode	Water depth (m)	Yield strength (Mpa)	Tensile strength (Mpa)	Elong. (%)	Charpy energy 0°C(J)	CTOD 0°C (mm)	Diffusible hydrogen (ml/100g)
A	1,5	405	463	17	41	0,78	18
B	1,5	418	477	20	48	-	-
B	12	-	490	-	35,2	-	-

Testes performed at depths of up to 35 m in cooperation with the GKSS to qualify procedures for class B weldings lived up to the requirements of the AWS D3.6 standard in the following aspects: a) mechanical resistance in shear strength tests and b) amount and size of the discontinuities like slag inclusions, pores and lack of fusion. However, such qualification of the proposed procedures was not attained due to the presence of weld metal root cracks, in 5F test specimens (diameter 400mm, thickness 22mm). The occurrence of such cracks (Figure 6) was also observed in the welding tests of sleeves on pipes, simulating the conditions existing in actual repairs. New studies are being undertaken in order to assess the significance of these cracks in the light of fracture mechanics (PD 6493). These results suggested that the AWS D3.6 standard be reanalized in terms of the definition of the joints geometries acceptable for qualifying the fillet welds, inasmuch as this joint type has shown to be sensitive to the occurrence of root cracks. Thus the qualification of fillet welds by means of butt welds, for instance, should be discussed.

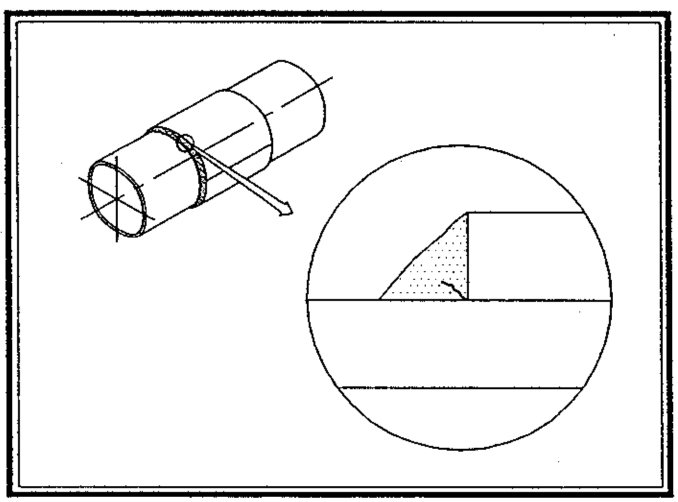

Fig 6: Schematic representation of the root cracks commonly observed in overlapping joints.

The use of the Flux cored arc welding process (FCAW) in wet environment has also been the subject of some studies initiated recently. These studies emphasize the need to look for a better understanding of the physical phenomena involved analysing the arc stability and metal transfer mechanisms. In view of its features this process has a great potential for application in wet welding due to the increase in productivity and the reduction of cold cracking risks.

FUTURE ACTIONS AND DEVELOPMENTS IN WET WELDING

The generalized acceptance of wet welding in structural application initially conflicts with the negative reputation in respect of the quality of such weldings. In order to overcome this barrier the Classification Societies can play a very important role. Apparently the Classification Societies have not been sufficiently involved in research and development projects so as to direct them more objectively toward the attainment of results which satisfy quality requirements to be jointly established. In this respect it would be of great important that a channel of discussion be created between the wet welding technical community and the Classification Societies with the purpose of defining lines of action and research areas leading to the acceptance of wet welding as a structural repair method.

In compliance with the results obtained by PETROBRÁS it is suggested that research and developments efforts concentrate initially on shallow waters (< 40 m) and that the following Shielded Metal Arc wet welding research areas should be considered prioritarian:

- Development of electrodes with higher toughness and lesser diffusible hydrogen content;

- Study of root cracks nucleation and propagation mechanisms during welding;

- Assessment of the significance of root defects.

As regards to other welding processes it is suggested that priority be given to the Flux Cored Arc Welding (FCAW) process.

DEVELOPMENTS IN HYPERBARIC WELDING

In terms of the input of technology, hyperbaric welding may be classified into three categories in the following growing complexity sequence: manual welding, diver assisted automated welding and fully automated welding.

Manual Welding

The maximum depth for using manual welding is related to the physiological aspects of human diving and thus commercially limited to about 300m. Therefore, the hyperbaric welding technology has been satisfactorily developed and applied in several parts of the world. That is why PETROBRÁS has not made investments in developing it in recent years.

Diver Assisted Automated Welding

In the specific case of pipeline repairs the use of diver assisted orbital systems is advantageous, because they allow for a lesser psycho-motor performance on the part of the welder during deep diving and ensure greater homogeneity and continuity in the welding. Furthermore, a productivity gain is achieved which makes it feasibe to employ low deposition rate processes, such as, for instance, the GTAW process. The root pass is the critical aspect in orbital welding because the preparation and the alignment of the joint are considerably more complex than at the surface. In cooperation with the GKSS (Germany) PETROBRÁS has performed a test campaigns in hyperbaric chamber at 50 bar in order to test the MOSS system developed by GKSS. The main result achieved was ascertaining the possibility of welding root passes with gaps of up to 5mm and qualify welding procedures down to 500 msw.

Fully Automated Welding

In the light of future deep water production prospects in Brazil an extensive network of pipelines shall be operating at water depths inaccessible to divers. An important issue that has to be considered is how to repair such pipelines. Hyperbaric welding above 50 bar has been little investigated. Recent test results with the GMAW process (solid wire and metal cored wire) between 50 bar and 110 bar carried out by PETROBRÁS and GKSS show that it is possible to obtain welded joints, in the flat position, with mechanical properties comparable to atmospheric welds (Figure 7). The main obstacle, however, to overcome is the instability of the electric arc that increases with pressure thus making difficult the positional welding. Hence, before a stage can be reached whereby fully automated repairs could be reliably performed, extensive research must be carried out. The study of the process variables shall be the focal point to achieve the objetive of establishing sets of parameters capable of providing a welding with satisfactory process stability. In view of the inexistence of a tested technology to execute deep waters repairs "in situ", PETROBRÁS has chosen to launch only small diameter lines that can be cut off and lifted to the surface for repair. However, the availability of a fully automated system for "in situ" interventions would provide important advantages and eliminate the restrictions concerning the diameter and the integrity of the pipeline to be repaired. PETROBRÁS is initiating some basic studies concerning the technical feasibility of such a system, comprising:

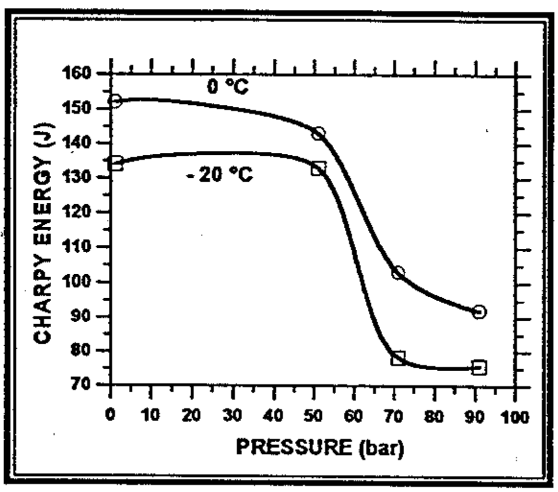

Fig. 7: Relationship between toughness and pressure

- Atmospheric tests, in a robotic cell controlled by an off-line programming system, with a view to the subsequent utilization of industrial robots in pipeline repair welding;

- Adapting an industrial robot to operate in hyperbaric conditions, up to 100 bar in a moist gaseous environment;

- Development of hyperbaric welding procedures in pressure of up to 100 bar with the GMAW process.

KEYNOTE ADDRESS FROM AN INTERNATIONAL CERTIFICATION AGENCY

PRACTICAL APPLICATIONS OF CERTIFICATION FOR UNDERWATER WELDING OPERATIONS

Rodger D. Holdsworth and Dr. Jack S. Spencer - American Bureau of Shipping

ABSTRACT

The paper illustrates how the use of systematized certification programs is an effective management tool to measure and improve performance. The paper describes how changes in management techniques, consumer concerns and technological trends have impacted the way the offshore industry purchases/provides products and services. Critical issues, such as the recognition of safety and environment, are discussed enforcing the argument for certification and exemplifying the benefits that are making certification programs a key part of business for the 21st Century.

1. INTRODUCTION

Certification is one of the most effective methods of lowering risk, improving quality and enhancing process controls crucial to underwater welding and construction projects.

Certification programs have withstood the test of time in determining, verifying, and attesting in writing to the qualifications of personnel, processes, procedures, equipment, consumables and/or other items in accordance with applicable requirements. The following sections discuss critical issues which enforce the need for systematized certification programs by duly authorized bodies and the advantages that certification can provide to subsea construction projects. The focus on quality, safety and the environment has never been stronger and continues to be of interest to governments, consumers, businesses, special interest groups and the news media. Demands placed on businesses to conform to multiple standards and changes in rules/regulations have influenced industry to reorganize and change buyer specifications, recommended practices, design criteria and other aspects of how products and services are provided.

Responding to specifications has meant delivering a product or service conforming to form, fit and function (hopefully on time and within budget). Today's business consciousness includes demonstrating:

◊ That quality system controls are compliant to customers specifications.
◊ That design, procedures, and instructions are documented, meet applicable standards, recommended practice and regulatory requirements.
◊ That training records are maintained on personnel responsible and accountable for work to be performed.

◊ That personnel are qualified to meet the application requirements and tasks assigned safely.
◊ That the mechanical integrity of equipment is maintained and documented.
◊ Verifying/certifying all of the above.

These type of requirements and what we, as an industry, must prepare for as needs emerge are the basis of this paper. Various managerial/business trends, "fashions", and technology that have influenced change in the offshore services industries are also reviewed. The following sections discuss how certification can satisfy the above stated demands for various industry groups such as commercial (offshore, ports/harbors, vessels), military (Navy), utilities (power plants, dams) and other industry group who use underwater welding services.

2. INDUSTRY TRENDS

Certification, once looked upon by many industries as a unwelcome requirement, is shifting to a desirable management tool. Changes in regulatory, finance, insurance, customer and other requirements have significantly affected the offshore industry organization, operations, quality systems and strategies to ensure future growth while establishing a safer, healthier work environment. The following sections outline the recent trends that have brought about industry need for a teaming approach through the use of systematized certification programs.

The introduction of quality management philosophies has significantly changed industry's view of company organization and processes in the 90's. Quality programs and systems, such as ISO 9000, Total Quality Management (TQM) and Total Quality Leadership (TQL) are impacting the way industry meets the needs of the customer.

"Stream-lining", "down-sizing" or what is often referred to as "right-sizing" are various reorganization methods intended to improve work processes, reduce unnecessary redundancies and optimize labor resources without loss of quality of service or product. Coupled with these changes in organization has been the need to retain and certify personnel when assigning additional responsibilities. "De-Layering" is another reorganization process which essentially alleviates several layers of what had been considered "check-stops" in organizing, qualifying and producing underwater welds. Management's ability to train personnel in quality techniques and "empower" its employees, has enabled owners and contractors to focus more attention at component levels without increasing the cost of labor. Making more efficient use of resources by diversifying the use of personnel has also helped to reshape organizations and maximize the use of resources.

Increased demands to satisfy multiple standards, rules and customer specifications, has led to process "re-engineering" to ensure compliance and satisfy new quality system requirements. Many companies are focusing more on their core business and out-sourcing processes to reduce cycle time and costs as well as improve the efficiency of work processes. One of the best opportunities for out-sourcing involves the quality functions, as this permits objective third-party organizations to assess performance and management systems. Risk and performance have become greater issues than productivity or timeliness, especially when the cost for non-compliance is significantly greater than redesign, inspection, or assessment.

To remain competitive, commercial diving companies are looking at techniques to reduce risk, improve safety and ensure compliance while meeting the needs of the customer. Some companies are restructuring their methods of operation, implementing total quality management techniques, quality systems (such as those which are certified to the ISO 9000 criteria) and increasing the use of quality trained/knowledgeable personnel in day to day operations.

In line with the re-engineering process, the former "nice-to-haves" and "need-to-haves" has been replaced by "where it needs to be". The redistribution of assets and justification of new assets is in response to the necessity offshore service industries to streamline operations, cut waste and control costs in the 90's.

Measurements of products and services have gone beyond past requirements. Customers are now verifying vendor control of quality of operations, conformance to specifications as well as federal, state and other standards before selecting a product or service.

3. ENGINEERED SYSTEMS AND TECHNOLOGY TRENDS

Design of engineered systems, equipment and consumables today must be made in accordance with recognized standards, be constructed of materials that meet application demands, demonstrate mechanical integrity, be able to withstand vigorous testing and inspection, have traceability on product components and be able to conform to a host of other criteria in order to meet today's customer demands. The dramatic pace at which technology has changed the business environment has contributed significantly to the increased industry need for systematized certification programs.

◊ Technology is becoming more powerful, flexible, and cost effective;
◊ Has fewer limiting factors;
◊ Requirements beyond original design parameters are viewed as performance constraints;
◊ International standards, codes, guidelines and specifications are not keeping pace;
◊ Operations and support issues are becoming more important in design considerations;
◊ "Standardization" and "Modularity" are increasing in importance.

Intensified customer demands are changing the corporate environment and increasing the role of recognized third party certification agencies that offer an effective means for companies to demonstrate:

◊ Control of quality of operation;
◊ Ability to meet customer and international requirements;
◊ Compliance of federal, state and regulatory requirements;
◊ Compliance to underwriter and special interest concerns, and
◊ Responsible care and safe practice

4. CERTIFICATION

For well over a century, before regulatory bodies were established, duly authorized certification agencies have played a key role in developing industry accepted standards, determining requirements, verifying compliance and attesting to conformance by documenting evidence of satisfaction.

The certification process is: One (1) based upon the requirements of customer specifications, applicable rules, national/international standards, industry codes of practice, or, when no standards exist, the manufacturer's standards and/or engineering analysis; two (2) confirmed by examination and provision of objective evidence that the requirements have been satisfied by both the customers specification and governing standards; and three (3) supported by evidence of satisfaction, and documented in the form of a Certificate of Conformity.

<u>CERTIFICATION</u>

<u>WHO?</u>

A Duly Authorized Body:

1. - First Party (Operator / Owner)
2. - Second Party (Contractor / Manufacturer)
3. - Third Party (Independent Agency or Individual) selected by the First and/or Second Party.

<u>WHAT?</u>

ACTIVITIES:

1. Determine
2. Verify
3. Attest To

<u>HOW?</u>

In accordance with applicable standards, specifications, codes, Manufacturer and Other Industry accepted practice.

<u>WHERE?</u>

1. Source (hardware, material, components, etc.)
2. Site (facility(s), management systems, etc.)

<u>WHEN?</u>

1. Before (Determine)
2. During (Verify)
3. After (Attest To)

Figure 1

How does the certification process apply to underwater welding operations? What activities are involved? What processes/items are assessed and what forms the basis for certification relative to commercial underwater welding?

Underwater welding projects generally have their own unique requirements and environmental constraints. It is important to have an overall project plan that coordinates the various tasks and provides a path to achieve the desired results. Figures 2, 3 and 4 illustrate key underwater welding program elements that play a part in the certification process. The certification of the overall process must be flexible enough to adjust to the facility, and other requirements, provide information to evaluate and attest to each phase of the project as outlined in the following sections.

5. PRODUCTION SPECIFICATION

5.1 Weldment Design

Underwater weldment designs are typically developed by the operator from data which may include:

◊ General Design Information.
◊ Construction and/or Service History.
◊ Operational (or process) Data and Requirements.
◊ As-Built Drawing.
◊ Periodic and Recent In-Service Inspection Reports and Findings.
◊ Final Engineering Analysis Information

While the above considerations are generally sufficient to develop design of underwater weldments, design engineers often finalize weldment design independent of the underwater welding and inspection groups. Design engineers seek assurance that their design will meet the requirements considering the constraints unique to underwater welding and the environment.

Systematized certification programs review design to ensure adherence to the applicable regulations, standards, codes, rules, practices, guidelines, etc. helping to prevent conflicts between the standards and the specification during the specification development phase.

5.2 Specification Plan

To develop the production specification, the operator(s) must determine:

◊ the end result required.
◊ the options available to assure fitness for purpose, feasibility, fabricationability, measurability, performance reliability, maintainability, environmental/safety aspects, time scale, life cycle cost and other related items.

- ◊ standards and requirements necessary to assure good workmanship.
- ◊ the associated risks.
- ◊ what material, type of services, processes, inspection, documentation and quality records will be required.

To assure the project's objectives will be in compliance with the standards specified, the operator needs to determine whether:

- ◊ the design is in compliance with applicable rules, national standards, industry codes of practice.
- ◊ the potential contractor(s) service capability, work process, and systems meet the qualification requirements.
- ◊ potential subcontractor(s) meet the qualification requirements.
- ◊ the material, equipment and consumables to be utilized meet the specified requirements.
- ◊ document and quality controls are sufficient to meet the requirements of the specification.

Independent Certification assessments promote an understanding of the requirements and standards by all parties and provide assurances to management, regulatory bodies and the contractor(s) themselves.

The need for consistency, quality documentation, evidence of due diligence and the lack of qualified resources make certification an effective option in meeting the challenges prevalent in most underwater welding operations.

6. PRODUCTION ORGANIZATION AND QUALIFICATION

Underwater welding is one of the most challenging of all welding processes. To organize, qualify and meet production requirements for underwater welding operations the contractor must:

- ◊ have a complete understanding of the contract specifications; applicable commercial diving, welding, inspection standards and regulations; and other applicable criteria.
- ◊ estimate and allocate the personnel, equipment and subcontractor resources required.
- ◊ procure material and consumables in accordance with specified requirements.
- ◊ develop and qualify procedures in accordance with specified requirements.
- ◊ review and verify that work processes conform to specified requirements.
- ◊ qualify and certify welding, inspection and field personnel to specified requirements.
- ◊ qualify subcontractors such as suppliers of vessels, barges, tugs, and other services and hardware to specified requirements.
- ◊ ensure that equipment such as welding machines, Pressure Vessels for Human Occupancy (PVHO's), umbilicals, hydraulic units, control stations, etc. are in suitable condition, and will meet the specified production requirements.

The contractor in some cases must organize resources to conform to specifications that may stretch the limits of their capability or the project teams ability to meet scheduled milestones. These situations call for new and innovative approaches that prevent delays before they happen, promote continuous improvement and help to ensure optimum use of equipment and qualified personnel.

To ensure meeting the project objectives, safely and on time, the contractor and other responsible parties need to verify:

◊ that material, equipment and consumables conform to the specified requirements.
◊ measuring, gauging and test equipment are calibrated in accordance to applicable standards and manufacturers recommended practice.
◊ applicable systems meet regulatory and other related requirements.
◊ welding, inspection and field personnel are qualified.
◊ processes, quality controls and data management meet the specified requirements.
◊ that subcontracted services, rental equipment and other sourced items meet the specified requirements.

While certification may not be a requirement, established independent certification programs are a cost effective means of accomplishing the above objectives. Certification programs can help maximize the project team's productivity, provide a checks and balances that help to ensure quality, safety, management confidence, as well as reduce the possibility of failure or non-conformance during production.

7. PRODUCTION

The production process for underwater welding operations requires the same knowledge requirements as surface welding operations in addition to meeting the challenges of the offshore environment. Documentation during the production process can mean the difference between success and failure in any underwater welding project. Operators depend upon field documentation to develop ongoing inspection plans, future modifications and evidence of satisfactory completion and/or conformance to requirements. All of the certification activities previously discussed are designed as a preventive, to either determine or verify conformance before the production phase.

Certification of underwater welding operations during and after production is designed to attest to the satisfactory completion of the work assigned at milestone points during production and after completion. The certification program sets guidelines for the documentation generated in accordance with the requirements for the project undertaken as well as other items that may be needed for future tasks such as: engineering analysis; in-service inspections; updating system and component drawings; etc. When tied with the documentation gathered during the project organization / qualification and production phases, the result is a comprehensive source of information invaluable to maintaining the future integrity of the facility repaired.

8. BENEFITS

The use of certification programs by duly authorized certification agencies offer a balanced alternative that surround and help to insulate the owner and contractor from the pit-falls of reorganization and change. Certification programs have a history of :

- ◊ Providing leverage to existing design.
- ◊ An effective management tool to benchmark performance.
- ◊ Providing a framework for existing systems that encourage continuous improvement, improve quality, safety, control of operations.
- ◊ Identifying risk and other areas of concern.
- ◊ Providing a means to pre-qualify vendors, assist as a third party in establishing partnerships and joint ventures through independent assessment.
- ◊ Serving large, medium and small companies.
- ◊ Providing a means to demonstrate due diligence, responsible care, safe practice and good management practice.
- ◊ Providing a means to demonstrate compliance to customer specifications, international and other requirements.
- ◊ Provide a common platform for companies with multiple facilities to evaluated and improve performance.
- ◊ Lowering insurance premiums through documented reduction of risk demonstrated over a period of time.
- ◊ Creating a fair, transparent set of rules to help level the playing field for industry.
- ◊ Providing transition opportunities.

Certification is a part of our lives that we may have taken for granted or not used to its maximum potential. Would travel be as safe and reliable today if planes, trains and automobiles were not inspected or certified? What risks would we incurr if hotels were not inspected by the Fire Marshall or restaurants were not inspected by the Board of Health? Certification lowers the risks we take in our day to day lives because we have agreed to minimum standards that help to control the risks. There is a need for a greater understanding of the role of certification and a increased reliance on certification to help lower risk, improve safety, enrich the environment and raise the level of quality in products and services. Better control of certification bodies is also needed to realize all of the potential benefits certification can provide.

9. SUMMARY

Concerns responsible for the various phases of underwater welding and other offshore construction projects seek a practical and effective means to lower risk, enhance process controls, and improve quality and safety in their operations. Today's industry trends focus on quality management philosophies that influence the way products and services are solicited and delivered, and have changed industries perception of certification as a uninvited requirement to a desired management tool.

Certification programs for underwater welding operations employ a quality systems approach that help determine design, and specification compliance, verify that project organization, qualification, production and documentation conform, and attest to the final product meeting the end results desired.

OWNER / REGULATORY AGENCY

CONCERNS

DESIGN

- General Design Information
- Construction / Service History
- Operational Data Requirements
- As-Built Drawings
- Engineering Analysis

SPECIFICATION PLAN

- End result required
- Options Available
- Standards and Requirements for Workmanship
- Associated Risks
- Material Processes; Consumables
- Resource Requirements (services, equipment, etc.)
- Documentation & Quality Record Requirements
- Procedures

CERTIFICATION AGENT

DETERMINE

DESIGN REVIEW

Compliance
Safety
Trend Analysis
History
Prospective Regulations

ASSESSMENT

Feasibility
Workmanship
Safety
Continuity
Materials
Qualifications
Completeness
Practical Application

CERTIFICATION POINTS - PHASE I

Figure 2

OWNER / CONTRACTOR

CONCERNS

PRODUCTION ORGANIZATION

- Understand Contract, Specification, Standards, Drawings, Regulations, etc.
- Allocate Resources, Personnel, Equipment, Subcontractors
- Procure Material, Consumables
- Develop Procedures
- Inspect and Maintanence Equipment
- Procedure and Process Instructions
- Finalize Indirect Requirements
- Complete Project, Inspection, Quality Control and Safety Planning
- Complete Data Management Plan

PRODUCTION QUALIFICATION

- Qualify Material and Consumables Conform
- Qualify Mechanical Integrity of Field Equipment
- Qualify Calibration of measuring, guaging and Test Equipment
- Qualify Systems Compliance to Regulatory and other Requirements
- Qualify Procedures, Welding, Inspection and Field Personnel
- Qualify Subcontractors (e.g. suppliers of vessels, barges, etc.)
- Qualify Processes, Quality Controls, Safety and other Requirements
- Qualify Documentation Plan, Forms and Reporting Requirements

CERTIFICATION AGENT

VERIFY

ASSESSMENT

Verification
Conform
Safety
Certify
History
Measure
Compare
Document
Support

WITNESS \ VERIFY

Bear Witness
Certify
Safety
Compare
Measure
Completeness
Document
Support

CERTIFICATION POINTS - PHASE II

Figure 3

OWNER / CONTRACTOR REGULATORY AGENCY

CONCERNS

PRODUCTION DOCUMENTATION

- Material and Consumable Records
- Quality Records
- Qualification Records
- Inspection Records
- Job log Records

PROJECT COMPLETION DOCUMENT

- Support Documentation

CERTIFICATION AGENT

ATTEST TO

VERIFY

Completeness
Document
Certify
History
Support

CERTIFY

Bear Witness
Support
Issue Certificate

CERTIFICATION POINTS - PHASE III

Figure 4

Theme Papers

State-of-the-Art And Practice Of Underwater Wet Welding of Steel

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I. INTRODUCTION

Underwater wet welding is conducted directly in water with the shielded metal arc(SMA) and flux cored arc (FCA) welding processes. Underwater wet welding has been demonstrated as an acceptable repair technique down to 100 meters (325 ft.) in depth, but wet welds have been attempted on carbon steel structures down to 200 meters (650 ft.).

The water environment acts as a fast quenching medium which hardens the heat affected zone making it susceptible to hydrogen cracking. For this reason, it has been shown that with few exceptions the wet underwater welding technique is limited to steels of low carbon equivalent (CE < 0.40 wt. pct.) (1). The carbon equivalent is typically given by the expression:

$$CE = C + \frac{Mn}{6} + \frac{(Cr + Mo + V)}{5} + \frac{(Ni + Cu)}{15} \tag{1}$$

The strength of the carbon steels used in the deeper structures is also important because higher strength steels (with over 350 MPa or 50 ksi minimum yield strength) are required at greater depths. These higher strength steels usually have higher carbon contents and thus higher carbon equivalents which make them more difficult to weld in water, especially those steels with a carbon equivalent greater than 0.40 wt. pct. The wet underwater welding of higher strength steels introduces more stringent requirements for acceptable heat affected zone properties, including concerns about hydrogen damage. It has been shown that high carbon equivalent steels when wet welded with ferritic electrodes are subject to hydrogen cracking of the heat affected zone (HAZ).

There is a major difference between wet and dry hyperbaric welding. Both experience increased pressure with depth (one bar for each ten meters increase in depth), but the wet environment also influences the cooling rate during welding which affects the nature of the weld metal phase transformations. Whereas surface covered electrode (SMA) welding has $\Delta t_{8/5}$ between 1 and 6 seconds, depending on heat input (20 to 90 kJ/in) and plate thickness (2-7). The influence of heat input on cooling time, $\Delta t_{8/5}$, for both dry and wet welding on various steel joint preparations is shown in Figure 1. Such a large cooling rate for wet welds produces significant amounts of HAZ martensite in nearly all low carbon steels. As the carbon equivalent of these steels approaches the value of 0.40 wt. pct. the fusion line hardness usually exceeds 400 Vickers (10 kg load). As the martensite content increases in the near fusion line region of the heat affect zone, the susceptibility to hydrogen cracking becomes a measurable concern.

The primary purpose of this paper is to document and evaluate current understanding of metallurgical behavior of underwater wet welds so that new welding consumables can be designed and new welding practices can be developed for fabrication and repair of high strength steel structures at greater depths. First the pyrometallurgical and physical metallurgy behaviors of underwater weldments will be discussed. Second, modifications of the welding consumables and processes will be suggested to enhance our ability to apply wet welding techniques.

Christensen (2), Masubuchi et al. (8-13), Dadian (14), Cotton (15,16), Grubbs (1, 17, 18), Watson et al. (19), and Ibarra et al. (20-29) have written extensive reviews of the technology and metallurgy of underwater welding. Some researches (30-35) have characterized the difficulties and the limitations on underwater welding. The basic concepts for underwater weld metal chemistry and metallurgy have also been introduced (2, 11, 20-24, 35-45). The most comprehensive fundamental investigations have been primarily on the influence of pressure on hyperbaric shielded metal arc weld metal compositions (2,10,36-38).

II. UNDERWATER WELDING PYROMETALLURGY

Effect of Pressure on Weld Metal Chemical Composition

Christensen et al. (36-37) have shown that with increasing pressure or depth weld metal manganese and silicon contents substantially decreased. The weld metal manganese experienced a 0.3 wt. pct. decrease from the surface composition at 30 bars (300 meters). Weld metal silicon decreased 0.10 wt. pct. with an increase of 8 bars or 80 meters in depth. Different from manganese and silicon, weld metal oxygen and carbon contents increased by factors greater than two when comparing composition of hyperbaric welds made at 300 meters to weld metal deposited on the surface. The weld metal oxygen increased from an acceptable 300 ppm to a questionable 750 ppm level. While manganese and carbon variations can cause significant changes in hardenability of the weld metal, high weld metal oxygen has been related to inferior weld metal toughness (29, 46-50).

Christensen et al. (2) indicated also that similar weld metal compositional variations should occur in wet underwater welding as shown in Figure 2. Mathisen and Gjermundsen (39) and Shlyamin and Dubova (51) reported similar variations in manganese and silicon contents for wet welds made down to 70 meters. They found only little variation in carbon for the depth range that they investigated.

Weld Metal Carbon-Oxygen Relationship

Ibarra et al. (20-24) and Wood et al. (52) have characterized wet underwater weld deposits down to 200 meters (650 ft.). The chemical compositions of wet SMA welds were evaluated by Ibarra et al. (20-24) as a function of depth (pressure) down to 200 meters (650 ft.). The weld metal manganese contents as a function of depth are given in Figure 3. Note the sharp decrease in manganese content from 0.6 wt. pct. for the surface weld to 0.25 wt. pct for the weld made at 30 m (90 ft.). This decrease in weld metal manganese content can be directly correlated to the rapid increase in weld metal oxygen content for the same range of depth shown in Figure 4. This observation suggests the manganese content is controlled by oxidation. Similar decreases in weld metal content were found for the weld metal silicon, as shown in Figure 3. It is to be expected that these oxide-forming elements would respond in this manner to the increase in oxygen. The weld metal carbon content, on the other hand, was found to increase significantly from the weld made at the surface to the weld made at 50 m (150 ft.), as shown in Figure 5.

Grong et al. (37) found in hyperbaric welding that weld metal carbon and oxygen contents related to the law of mass action for the carbon monoxide reaction, that is:

$$CO(g) = \underline{C} + \underline{O} \tag{2}$$

and the equilibrium constant, K, is approximately equal to:

$$K = \frac{[C]\,[O]}{P_{CO}} \tag{3}$$

The partial pressure of carbon monoxide, P_{CO}, is related to the total plasma pressure, P, through Dalton's Law;

$$P_{CO} = X_{CO}P \tag{4}$$

where X_{CO} is the fraction of the welding arc atmosphere. Substituting and rearranging Equations 3 and 4, the product of the weld metal carbon content, [C], and weld metal oxygen content, [O], is then given by:

$$[C]\ [O] = KX_{CO}P = k'P \tag{5}$$

where k' is a constant.

An important consequence of the calcium carbonate additions to the flux covering was the decarburization that resulted (54) as shown in Figure 6. Note that as the amount of calcium carbonate in the covering increases, the weld metal carbon content decreased. As calcium carbonate decomposes, several gases are formed including CO, Co_2, and O_2. A plot of the equilibrium line for carbon and oxygen at 1 atm pressure at 1873 K is shown in Figure 7. The results from chemical analysis of the underwater welds are also shown in this figure. Notice that the two curves are fairly parallel which provides further evidence that the CO reaction was in control. the displacement of the experimental curve to higher values is consistent with the high temperatures experienced in the arc (5000 to 20,000 K) and the higher pressure due to the water head (2 atm).

Grong et al. (37) found a linear relationship between this [C] [O] product and the total pressure, P, or depth for the SMA hyperbaric welding. Using the assumption that the weld metal composition has some information of quenched-in high temperature reactions, but also recognizing that welding is neither isothermal or at equilibrium, the plot of the product [C] [O] would be expected to be a linear function of the total pressure if the C-O reaction is controlling. This behavior was observed for hyperbaric SMA welding down to the equivalent of 300 meters in depth. Since carbon monoxide is a product of the decomposition of the calcium or manganese carbonate in the SMA electrode coating, the resulting increases in the weld metal oxygen and carbon contents suggest concerns about using flux coating containing carbonates for hyperbaric welding. Welds performed in deep waters would pick up oxygen and carbon which could alter the weld metal microstructure and properties. They also found that ferro-silicon addition to the flux indeed reduced weld metal oxygen, but not sufficiently to alleviate this problem.

To evaluate whether the carbon monoxide reaction is controlling in wet underwater welding the [C] [O] product for these wet underwater welds was also plotted by Ibarra et al. (23) as a function of depth (pressure). An excellent linear correlation was found for the weld metal carbon and oxygen products for welds down to 50 meters (160 feet) (Figure 8). this observation suggests that the carbon monoxide reaction controls the oxygen content down to approximately 50 meters (160 feet), and the oxygen content, in turn, controls the oxidation of alloying elements such as manganese and silicon, and thus, their weld metal contents.

Weld Metal Hydrogen-Oxygen relationship

Between 50 meters (160 ft.) and 200 meters (650 ft.), the weld metal oxygen and carbon contents become fairly constant (53), Figure 8. Notice also that the weld metal manganese and silicon contents are fairly constant between 50 meters (160 ft.) and 200 meters (625 ft.), Figure 3. This observation suggests that the oxygen monoxide reaction is not the controlling reaction at depths greater than 50 meters (160 ft.).

The compositional results for depths greater than 50 meters 9160 ft.) suggest that the H_2O decompositon reaction may be the controlling reaction. At high temperatures water vapor dissociates into hydrogen and oxygen (32):

$$H_2O_{(v)} = H_{2\,(g)} + \frac{1}{2}O_{2\,(g)} \tag{6}$$

It is assumed that the oxygén will react with thė weld metal droplet or weld pool by the reaction:

$$\frac{1}{2}O_2(g) \rightarrow \underline{O} \tag{7}$$

where $\underline{O}$ is the weld metal oxygen content. This dissolution reaction results in the following controlling reaction:

$$H_2O\,(g) = H_2\,(g) + \underline{O} \tag{8}$$

The law of mass action for this reaction is given by:

$$K_2 = \frac{P_{H2}\,[O]}{P_{H2O}} \tag{9}$$

where K_2 is the equilibrium constant for the H_2O decomposition reaction (Equation 8), P_{H2} is the partial pressure of hydrogen and P_{H2O} is the partial pressure of water vapor. Using Dalton's law,

$$P_{H2O} = X_{H2O}P \tag{10}$$

$$P_{H2} = X_{H2}P \tag{11}$$

where X_{H2O} is the fraction of water vapor, X_{H2} is the fraction of hydrogen in the weld arc, and P is the total pressure which is directly related to depth. By substituting and rearranging the above equations, the following equation results:

$$K = \frac{X_{H2}P\,[O]}{X_{H2O}P} = \frac{X_{H2}\,[O]}{X_{H2O}} \tag{12}$$

From Equation 12, it can ben seen that the weld metal oxygen content will remain constant if X_{H2} and X_{H2O} are not a function of pressure or water depth. With constant oxygen content in the weld pool, the oxidation rate is expected to be constant and the [C] [O] product will also remain constant. If the suggested Equation 8 is the source of weld pool hydrogen it can be expected that as the depth or pressure increases the size of the plasma bubble (arc plasma column)
will decrease with the water content increasing as a component in the plasma. Tsai and Masubuchi (8) have found that the diameter of the arc plasma column decreases with increases in pressure (depth). Thus, at depths greater than 50 meters (160 feet) the [C] [O] product becomes less dominant and insensitive to depth as seen in Figure 8.

Another indication that hydrogen is more abundant and involved in the rate control chemistry is that the arc stability also decreases in extreme depth. It can be seen in Figure 9 that the parameter space for underwater welding decreases with depth. This behavior can be explained by the high ionization potential for hydrogen which makes it more difficult to sustain the welding arc.

Weld Metal Iron-Oxygen Relationship

Pope et al. (56) offered an alternate interpretation to the [C] [O] plateau in Figure 8. They attributed the oxygen "saturation" content in Figure 4 to the formation of FeO in the weld pool. The level of this oxygen saturation plateau is determined by the weld pool temperature and by the solubility limit of oxygen in liquid iron (approximately 0.2 wt. pct.) as can be seen in the Fe-O diagram, Figure 10. Hence, for an oxygen content above the limit of solubility, liquid FeO is formed as an immiscible phase with liquid iron. The presence of FeO dendrites in inclusions has been determined which supports their proposed model.

Effect of Titanium and Boron Additions on Weld Metal Chemistry

Titanium and boron, being strong deoxidizers, were observed to influence significantly the weld metal oxygen content, and the amounts of important hardenability elements such as manganese and silicon. Sanchez et al. (54) observed that even when the ferro-manganese content in underwater wet welding electrodes was maintained constant (at approximately 6 wt. pct.), there was a wide variation in the weld metal manganese content. As shown in Figure 11, the weld metal manganese content of underwater wet welds is a strong function of the titanium content present. For an increase of 200 ppm of titanium, an increase of over 2000 ppm of manganese was observed. The increase in manganese led to an increase in acicular ferrite. titanium also influenced the recovery of silicon, with an increase of over 6000 ppm in weld metal silicon content in the same range of titanium additions (Figure 11). However, the excessive increase in silicon content is actually detrimental to the toughness of the weld metal.

Effect of titanium and Boron Additions on Weld Metal Oxygen

The underwater weld metal ~~oxygen content~~ is plotted as a function of weld metal titanium and boron content in Figure 12. Notice that at low titanium and boron concentrations, the weld metal oxygen concentration can be quite high, on the order of 800 ppm. As the titanium and boron concentrations increased, the weld metal oxygen content decreased, which agreed with the oxidation potential of these elements.

Conclusions (Section II.)

The basic framework for understanding compositional variations in underwater wet welds has been established. Chemical composition of wet welds was characterized (53) as a function of depth down to 650 feet. The current theoretical approach uses simple chemical reactions to explain the overall weld pool pyrometallurgy. The chemistry which controls weld compositions has been correlated to the C-O reaction for wet welding down to 150 feet. In this depth range increasing depth results in carbon and oxygen pickup in the weld pool which leads to losses of manganese and silicon. At depths greater than 50 meters, evidence of constant elemental compositions has been related to two possible controlling reactions in the weld pool. With increasing depth, the CO controlling reaction gives way to the H_2O or FeO formation reaction. In the case of FeO-Fe equilibrium, the weld pool becomes saturated with oxygen to form FeO in liquid iron. This change of mechanism with depth illustrates that there are multiple reactions occurring in parallel or in series. The interrelations between these reactions must be determined if consumables and welding practice are to be developed to achieve acceptable mechanical properties at all depth. The weld pool chemistry must be fully established, to the level that allows consumable manufacturers the ability to develop the needed electrodes and the users to select the proper electrodes for a specific depth.

III. MICROSTRUCTURAL DEVELOPMENT OF UNDERWATER WELDS

Low carbon steel weld metal microstructure consists of various fractions of ferrite, bainite (aligned carbides), and martensite (47). The weld microstructure shows characteristics of the solidification process with long dendritic or cellular-dendritic grain growth from the edges of the weld pool toward the center of the weld bead. There are three types of ferrite associated with weld metal: grain boundary ferrite (GBF), sideplate ferrite (SPF) and acicular ferrite (AF). Grain boundaries can promote the formation of large grain boundary ferrite (GBF), but are also the sites for the nucleation and growth of Widmanstatten or sideplate ferrite (SPF) which protrudes from the grain boundaries into the prior austenite grains. Acicular ferrite (AF) forms inside the prior austenite grains and has a much finer basket-weave type structure. Other microconstituents, such as pearlite, cementite and martensite, may also result. At faster cooling rates, the makeup of the weld metal microstructure will consist of increased amounts of bainitic/aligned carbide (AC) and martensitic structure, with decreased amounts of ferrites.

It is recognized that acicular ferrite is the microstructural constituent which gives high resistance to cleavage fracture in low carbon structural steel weldments (25-28,45). Factors leading to an increase in the volume fraction of this constituent usually improve weld metal toughness. The promotion of acicular ferrite should result from the proper amount of undercooling achieved through alternations in weld metal chemical composition. Hardenability agents such as manganese are effective in increasing the amount of acicular ferrite in weld metal. Microalloyed additions of titanium and boron are also known to promote intergranular ferrite. Boron inhibits the formation of grain boundary ferrite and titanium oxide promotes the formation of acicular ferrite. For optimal strength and toughness, the microstructures to be avoided are those with a high percentage of grain boundary ferrite, which result from a small degree of undercooling, and those which contain martensite, which result from a large degree of undercooling.

Continuous cooling transformation (CCT) diagrams can be used to explain the relationship between the welding process (its resulting cooling rate), the weld metal (base metal and welding consumables) chemical composition, welding environment, and the weld metal microstructure. Figure 13 illustrates a schematic CCT diagram for a low carbon low alloy steel weld metal. Also shown in this diagram is a specific cooling curve that intersects the ferrite nucleation curve at the acicular ferrite region. if the cooling rate was much slower, the cooling curve would intersect the grain boundary ferrite curve. At fast cooling rate the cooling curve intersects the bainite or martensite curves as illustrated. With this diagram it is possible to predict the trends for microstructural changes that would occur with a change in cooling rate.

Variations in weld metal oxygen and manganese will cause shifts in the transformation start (nucleation) curves in the CCT diagram as suggested in Figure 14. This increase in nucleation potential shifts the curves to shorter times, which can alter the weld metal microstructure and mechanical properties. Increasing manganese causes an increase in hardenability and austenite stability which will shift the ferrite transformation curves to longer times. CCT diagrams can be used to understand and assist in modifying the alloy composition of the welding consumables such that the acicular ferrite window in the CCT diagram intersects the cooling curve to maximize its formation and toughness of the weld metal. Specifying a correct weld metal composition can manage the effects of a severe quench due to the wet environment on weld metal microstructure.

The relative amounts of each ferrite morphology, which were measured for wet welds down to 100 meters (300 ft.), are reported in Figure 15. At depths near the surface the weld metal is primarily grain boundary ferrite with 10 to 20 vol. pct. upper bainite. With increasing depths, the relative amount of primary grain boundary ferrite decreases to about 50 pct., with increasing amounts of upper bainite and sideplate ferrite. Similar to weld metal composition, the major changes in microstructure occurred in the first 50 meters of depth. At depths greater than 50 meters the weld metal microstructure remained fairly constant. This result is consistent with the observation of a constant weld metal oxygen content which suggests a constant oxidation rate.

Instead of the predominately grain boundary ferrite and the sideplate ferrite microstructure, a weld metal with high volume fraction of acicular ferrite would result in better toughness. Sideplate ferrite has a lath formation mechanism similar to that of acicular ferrite, but it nucleates on existing grain boundary ferrite and grows into the remaining austenite. Acicular ferrite, on the other hand, nucleates on inclusions under specific conditions. The E6013 mild steel electrode, commonly used in underwater welding, does not produce the necessary weld metal composition to form acicular ferrite and sideplate ferrite results.

Acicular ferrite formation in underwater wet welds is possible, but only with controlled weld metal alloying additions, such as titanium and boron with the proper weld metal oxygen and manganese contents. Liu et al. (55) have successfully modified SMA underwater electrodes to introduce titanium and boron additions to the weld pool which resulted in high acicular ferrite content.

Figure 16 is a proposed schematic CCT diagram indicating the nucleation curves for the various ferrite morphologies and their positions to explain the microstructural changes as a function of pressure or depth. The increase in the amount of sideplate ferrite with increasing depth (Figure 15) suggests that an increase in the weld metal carbon content with increasing depth promotes greater hardenability and moves the sideplate ferrite curve of the CCT diagram to longer times. The carbon increase counteracts the influence of the reduction in weld metal manganese content and the increase in weld metal oxygen content. Further, the position of the sideplate ferrite domain relative to the acicular ferrite domain on the proposed schematic CCT diagram suggests that with increasing hardenability (e.g., through the addition of manganese), the curves can be sufficiently moved to the right to form some acicular ferrite.

Olson and Ibarra (21) suggested using a weld metal oxygen-manganese diagram to predict weldmetal microstructure with these complex compositional variations. They used effective weld metal manganese content, in the form of (Mn+6C), to combine the effect of the major hardenability elements, manganese and carbon. Figure 17 illustrates that for a given heat input, and thus cooling rate, there is a specific compositional range in weld metal carbon, manganese and oxygen to achieve optimal toughness. This region is illustrated by the hatched range in the figure. The shape of this range follows the results reported by Kikuta et al. (57). A diagram for the deposit of an underwater wet E6013 electrode is shown in Figure 18. The diagram was constructed based on the microstructural and compositional analysis, and represents a cooling rate found typically in wet welding in the Gulf of Mexico. Notice that this diagram suggests that attainment of the desired acicular ferrite requires increases in both weld metal oxygen and manganese. This graphical understanding should increase our ability to design new underwater welding electrode formulations to improve wet weld quality at greater depths.

Effect of Titanium and Boron on Weld Metal Hardness

As discussed previously, manganese and silicon pickup in underwater wet welds resulted in increased hardenability. Figure 19 (54) shows the increase in weld metal hardness as a result of increasing titanium and boron. The highest and lowest hardness peaks are related to the weld metal microstructure. The promotion of soft phases and hardenability increase are competing processes with the addition of titanium and boron. This relationship will be further discussed in the next section.

Effect of Titanium and Boron on Weld Metal Microstructure

A contour plot of the volume fraction of acicular ferrite in underwater wet welds as a function of titanium and boron (54) is shown in Figure 20. Notice the acicular ferrite peak (over 60 vol. pct.) at approximately 300 ppm hardness shown in Figure 19, indicating the effect of microstructure on weld metal mechanical properties. With increasing amounts of titanium and boron, above 350 ppm and 30 ppm, respectively, weld metal hardenability becomes excessive and the formation of martensite and microconstituents is promoted, Figure 21. Comparison with Figures 19 and 21 shows that martensite and microconstituents formation is responsible for the hardness increase observed.

Comparing the contour plot, Figure 20, with the results reported by Oh and Olson (58), it can be seen that the optimal ranges of titanium and boron for maximum acicular ferrite are displaced to lower titanium and boron compositions. The shift can be interpreted as the result of increased cooling rate in underwater wet welding which decreases the need for titanium and boron to optimize the acicular ferrite content.

When examining the effect of alloying elements on weld metal microstructure and properties, the P_{cm} hardenability formula developed by Ito and Bessyo (59) seems to be an appropriate tool.

$$P_{cm} = C + \frac{Si}{30} + \frac{Mn+Cu+Cr}{20} + \frac{Ni}{60} + \frac{Mo}{15} + \frac{V}{10} + 5B \tag{13}$$

Figure 22 shows (54) the hardness of underwater wet welds increased linearly with P_{cm}. Notice that some welds have hardness values above 30 Rc which is close to the hardness of martensitic steels with 0.08 wt. pct. carbon. As mentioned previously, the amount of acicular ferrite found in a weld metal will depend strongly on the inclusion size and size distribution. Therefore, one can expect variations in acicular ferrite content for a given P_{cm} as shown in Figure 23. It can be seen that as P_{cm} increases to approximately 0.17 wt. pct, the amount of acicular ferrite increase to a maximum. The weld metal hardness at the maximum acicular ferrite content is around 28 to 29 Rc. Further increases in P_{cm} were observed to decrease acicular ferrite. At approximately 0.19 to 0.20 wt. pct. P_{cm}, there is a considerable drop in acicular ferrite because of excessive hardenability which promotes the formation of ferrite with second phase and martensite phases. The variation of volume fraction of acicular ferrite can be explained as a function of the amount of ferrite with second phase and grain boundary ferrite, Figure 24.

Effect of Calcium Carbonate on Weld Metal Microstructure and Properties

The observed decarburization with increasing calcium carbonate additions resulted in a decrease in weld metal hardness (54), as shown in Figure 25. The reduced hardenability led to the formation of grain boundary ferrite. Figure 26 shows that when calcium carbonate additions increased, the volume ferrite with second phase and, to a lesser extent, martensite. The volume fraction of acicular ferrite did not vary significantly and did not exceed 12 vol. pct. The results are consistent with the low ferro-titanium and ferro-boron additions to the covering (2.4 and 0.4 wt. pct., respectively) and the low hardenability of these welds.

Conclusions (Section III)

The weld metal microstructure corresponds well to the established concepts when considering the compositional variations experienced with changing depth and the severe cooling rate in the water environment. At great depths other factors affect the thermal experience of underwater wet welding. These factors, which include plasma size and arc stability, must be fully characterized and modeled if welding consumables and practices are to be developed for achieving acceptable welds at these greater depths. Electrode diameter and flux coating thickness can become important parameters to achieve wet welds at greater depths.

Further microstructural characterization of wet welds must also be performed as a function of consumable composition, depth, and welding parameters. Quantitative computer models must be developed to allow easy prediction of weld metal microstructure and properties.

IV. HYDROGEN MITIGATION

Susceptibility to hydrogen cracking is a concern for surface welds as the strength increases above 350 MPa (50 ksi), but it can be controlled by the proper selection of welding procedures and consumables (60). Since moisture drastically increases the availability of hydrogen, wet underwater welds on higher strength steels are very susceptible to hydrogen cracking (61).

Heat affected zone hydrogen-induced cracking occurs as a result of three factors: 1) hydrogen pickup in the weld pool, 2) hard microstructures that develop in the HAZ, and 3) thermal and transformation stresses that develop in the weld joint. To eliminate the cracking the effect of these factors on the weld joint must be minimized. Examples will be given later to illustrate how changes to each of these factors can be used to improve the integrity of wet welding repairs on higher carbon equivalent steels.

The three possible methods to reduce or manage weld metal hydrogen content are: 1) to use consumables which can hold a high concentration of hydrogen in molten weld pools as well as in the solidified weld bead, 2) to alter fluxes to introduce alternate gases in the welding plasma, thereby reducing the hydrogen content, and 3) to select welding parameters which minimize weld pool hydrogen pickup.

Weld Metals with Enhanced Hydrogen Solubility

The use of ferritic base weld deposits will result in hydrogen rejection from the weld deposit into the fully martensitic heat affected zone which promotes underbead cracking. A method to alleviate somewhat the hydrogen susceptibility problem is to use an austenitic weld deposit which has a much larger solubility for hydrogen and thus less tendency to transport hydrogen to the heat affected zone (33,62).

The use of austenitic stainless steel consumables produces deposits with high thermal expansion coefficients relative to the ferritic base metal, which results in higher residual stresses and increased tendency for diffusion zone cracking. The compromise solution between high solubility for hydrogen and thermal expansion mismatch is the use of high nickel weld deposits since nickel base alloys have approximately the same thermal expansion as ferritic steel and are capable of managing a large hydrogen content.

The thermal expansion compatibility between the weld deposit and the base metal can be evaluated from Figure 27 (63-64). Note the large difference in thermal expansion between austenitic stainless steels (Point S) and the ferritic steel (Point F), and the similarity between the high nickel alloy (Point N) and the ferritic steel (Point F).

Even though the nickel weld metal deposit is virtually immune to the restraint cracking noted in the austenitic stainless steel welds, the use of nickel base electrodes is restricted by their depth sensitivity, with porous welds and embrittlement susceptibility. Excessive porosity have been reported in nickel base welds made at 33 meters (100 ft.) depth as a result of lack of heat input at these depths. Nickel base wet weld deposits have been successful down to ten meters when welded with the SMAW process. A higher heat input is required to make nickel base consumables behave properly and leave an acceptable weld deposit. Changes in the chemical compositions of the coating or changes in electrode diameters could be considered for improving heat inputs. Recently it has been reported (64) that Soviet investigators have deposited successful wet underwater welds down to 200 meters using a flux cored nickel wire. A cored wire allows for additions to be made into the welding plasma which assists the deposition process. These additions can increase the arc weldability and/or promote more heat through thermic reactions. The use of improved power sources should also be considered to improve the heat input for nickel base electrodes.

Weld Systems with Decreased Hydrogen in the Arc

To reduce the influence of the plasma hydrogen content, other gases must be introduced in the arc. It is known that increasing the carbonate content of welding flux increases the CO content in the arc and thus reduces the hydrogen content (65-66). Figure 28 illustrates the reduction of weld metal hydrogen in surface welds with increasing $CaCO_3$ contents in the flux. Similarly, increasing the carbonate contents of wet underwater electrode coatings should also allow for arc stability (because of larger number of charge carriers in the shielding gas) at greater depths and for the reduction of weld metal hydrogen content and porosity (decrease of hydrogen partial pressure). The influence of increased carbonate content in the electrode coating is expected to increase the depth at which the CO reaction is controlling as illustrated in Figure 29.

The use of carbonates to reduce the plasma hydrogen content does, however, promote the problem of weld metal carbon and oxygen pickup with increasing pressure. Carbon has been reported to reduce the hydrogen solubility in ferrite and increase the hydrogen solubility in austenite. Thus, increasing carbon content will potentially cause greater hydrogen supersaturation with the decomposition of austenite, thus reducing the favorable hydrogen reduction effects in the arc. This problem could limit the use of increased carbonate content to the more shallow depths.

Another factor affecting the use of carbonates can be seen from the work of Sorokin and Sidlin (66). They have reported that with an increase in the degree of oxidation of the deposited metal, the weld metal hydrogen content decreases. The relationship between weld metal oxygen and hydrogen contents is seen in Figure 30. It is apparent that with increasing weld metal oxygen content there is a significant reduction in weld metal hydrogen. This observation can also explain the influence of carbonate addition to the electrode covering since oxygen is produced with the decomposition of carbonates. The hydrogen content of the deposited metal can be reduced by increasing the $CaCO_3$ content of the coating.

Several investigators (67-68) reported that hydrogen cracking in underwater welding could be avoided by the use of oxidizing electrodes. Pope et al. (56) reported that underwater wet welds made with oxidizing electrodes had the lowest total hydrogen content (diffusible and residual). This measured total hydrogen represents the amount of hydrogen present in the weld metal just after cooling to room temperature. It seems logical to accept that the low hydrogen content is due to the hydrogen-oxygen controlling reaction in the weld pool.

It was also reported that alloying the weld deposit with chromium, molybdenum, and tungsten can reduce the hydrogen content. Niobium, as a strong deoxidant, increases the hydrogen content. Electrodes containing ten wt. pt. $CaCO_3$ in the coating showed that, on the basis of their capacity to inhibit the process of pore formation, the alloying elements can be arranged in the following sequence of decreasing porosity: titanium, niobium, manganese, rhenium, molybdenum and tungsten (63). Thus, reducing the hydrogen content should also reduce the tendency for porosity. Figure 31 illustrates the synergistic effect of weld metal niobium and manganese pore formation (66). For carbonate-containing electrodes there is an increasing weld metal oxygen content with increasing depth and a tendency to decrease weld porosity.

Hoffmeister and Kuster (40-41) reported that hydrogen pickup increased with the coating thickness of rutile electrodes used in wet underwater SMA welding, but decreased with heat input. A core wire diameter was used with various coating thicknesses varying the total electrode thickness from 7 to 10 mm. The HAZ hardness also was reported to increase with coating thickness. They produced weld metal CVN toughness values of 35 to 40 Joules at 0°C, by applying multilayer stringer beads using a low heat input.

It may also be possible to use zeolite type materials in the electrode coating and charge these minerals with argon and helium (39). Zeolites can physically absorb and store large volumes of gas elements in its crystal structure. When the zeolite materials decompose in the arc they will release the stored gases into the arc, and thus reduce the hydrogen content.

Effect of Welding Parameters on the Weld Metal Hydrogen Content

Madatov (69) reported the influence of welding parameters on the underwater welding processes and on the metallurgical reactions. Recently Soviet investigators (70) have shown the strong relationship between weld metal hydrogen content and welding parameters (welding potential and current). Figure 32 illustrates the variation in weld metal diffusible hydrogen content as a function of welding voltage. It can be seen that the hydrogen content increases with increasing voltage. Also weld metal diffusible hydrogen content was found to decrease with increasing welding current as shown in Figure 33. These results suggest that welding with lower potential and higher current will promote a significant reduction in weld metal diffusible hydrogen content (70). Hoffmeister and Kuster (40-41) have also reported that the diffusible hydrogen content in wet underwater welds decreases with increasing heat input as shown in figure 34 for SMA welding and Figure 35 for FCA welding.

A possible explanation of the influence of welding parameters on weld metal content is an electrochemical perturbance in DC arc welding. Welding pyrometallurgy during DC arc welding has been found to be a combination of electrochemistry and thermochemistry (71-73). It has been found that electrochemical half-cell reactions occur at the electrodes (the electrode tip and the weld pool). Figure 36 illustrates the DCEP arc welding processes as an electrochemical cell. An example of a cathode reaction in the welding arc can be the following:

$$H^{+} + e^{-} = H \tag{14}$$

It is apparent that the cathode surface could pick up hydrogen from the plasma by the above reaction. Another important variable is the current density which influences the efficiency and the rate of the electrochemical process. The electrode tip has a higher current density than the weld pool and thus electrochemical reactions will contribute more at an electrode tip than at the weld pool surface.

The suggested model for weld pool chemistry occurs in the following order. The compositions of liquid metal at the end of the electrode is altered by electrochemical reactions. In the form of droplets, this altered metal is transferred to the weld pool, modifying its composition. A back thermochemical reaction attempts to bring the chemically perturbed weld pool composition back to chemical equilibrium. The degree to which the weld pool can approach equilibrium depends on the time available for this back-reaction to occur, and thus depends upon the size of weld bead (heat input) and travel speed. In wet underwater welding the time for the thermochemical reaction is short. As a result, the weld metal composition is expected to be strongly influenced by the electrochemical reaction.

This model suggests that selection of welding current and polarity (direct current electrode negative - DCEN or direct current electrode positive - DCEP) is important to maintain an acceptable weld metal composition for wet underwater welding. The model also suggests that DCEN would produce less of a weld metal composition variation as a function of depth than DCEP. The use of DCEN should be investigated for wet underwater DCEN type electrodes. Underwater wet pulsed DC arc welding with a continuous arc should also be investigated to optimize the heat input and composition requirements.

The third factor that influences hydrogen cracking is the applied and residual stress state. The applied stress can be reduced by improving the fit-up on the weld joint to be used in the repair. In the underwater wet welding repair of platforms, scalloped sleeves are frequently fillet welded over the damaged area. Careful fabrication of the scalloped sleeves will result in improved fit-up and thus reduced stresses. The applied stress on a weldment can also be improved by using sufficient weld metal deposit to support the required load. This practice will result in a large HAZ with a smaller applied stress.

The residual stresses are more difficult to manage in an environment which is not easily accessible to postweld heat treatment. Welding practices that can reduce residual stresses include: 1) the use of small weld deposits, 2) the use of consumables with compatible coefficients of thermal expansion with the base materials, and 3) the selection of edge preparations which reduce the size of the total weld deposit. The cross-sectional area of the total weld deposit is directly related to tendency for shrinkage.

Further methods to reduce stress, and thus hydrogen cracking, must consider the thermal experience or experiences of the wet welding practice (74). It is very difficult to perform any significant preheat treatment procedures to the base material in heavy-section wet welding. A promising approach being investigated is the use of temper bead practice to reduce the near-fusion-line cracking tendency. Temper bead practice is typically a weld deposition that is laid down over a previous weld deposit which has a less susceptible cracking tendency than the base metal (75). An illustration of temper bead practice is shown in Figure 37. the second deposition (or temper bead) must be carefully located relative to the previous bead fusion line such that its thermal experience tempers the near-fusion-line heat affected zone of the base materials which has a cracking susceptible carbon equivalent (75). Evidence that temper weld beads can influence properties of wet underwater welds is shown in Figures 38 and 39 where weld metal Charpy V-notch toughness can be seen to improve with increasing number of weld passes (40-41). Using the above suggestions to reudce residual stresses as well as hardness in conjunction with a temper bead practice most likely represents the optimum practice to wet weld higher carbon equivalent steels.

A temper bead procedure of wet underwater welding with a measurable reduction of fusion line and near-fusion-line hardness has been reported (64,75). Samples from a platform steel with a CE of 0.42 wt. pct. were welded in a 10 meters (33 ft.) tank. A microscopic examination of the weldment revealed extensive hydrogen cracking and HAZ hardness values in excess of 450 Vickers (10 kg load). When the temper bead procedure was used after each pass, the HAZ hardness values had decreased to the 300 Vickers (10 kg load) range. Side bend tests were conducted on these samples and the results showed that the samples were of acceptable quality. The reduction in hardness indicates that a HAZ microstructure less susceptible to hydrogen cracking was obtained.

Another advantage to the temper bead practice is that while the temper bead is in the high temperature austenite condition it is a favorable reservoir for hydrogen and thus extracts some of the hydrogen from the more crack susceptible base metal HAZ.

Further advancements can also be made by introducing metal additions to the welding consumables which reduce a thermic reaction. Thermic welding has long been used to attach sacrificial anodes to pipelines and structures. These exothermic reactions will add heat to the arc welding process and will assist in making up for the loss of effective heat input due to increased depth or pressure. The metallic addition for the thermal reaction must be an element which reacts with oxygen or oxides and must have a very large negative heat of reaction. Examples of thermic additions are aluminum, lithium, calcium, and magnesium. The last three elements are virtually insoluble in steel and should not interfere with the steel composition as an alloy addition. They take part only in the desired heat-producing reactions. Thermic additions may be introduced as a metallic filler into a hollow rod electrode or as a powder addition in the electrode covering. Electrodes that contain thermic additions should also assist in alleviating problems in deep water wet welding with nickel base electrodes.

Chemical heat generating welding consumables have recently been investigated as an additional heat source during underwater welding (64). Samples from a platform steel with a CE of 0.42 wt. pct. were welded in a ten meter (33 ft.) tank. A heat-generating thermic electrode was used after each pass to postweld heat treat the heat affect zone.

Conclusions (Section IV)

Successful management of weld metal hydrogen, and thus cold cracking susceptibility of a base plate, is becoming a significant barrier to the mechanical integrity of underwater wet welds. Till recently the concern over hydrogen damage has not limited the use of wet welding. This tolerance to potential hydrogen pickup has been accepted due to the common use of lower strength steels with low carbon equivalents. To assure more far reaching use of this technique, hydrogen pickup measurement and damage must be studied and new methods to manage hydrogen need to be developed.

The influence of welding techniques, parameters and wet environments has only been partially characterized. From the existing data there are many important correlations. The weld metal hydrogen content is clearly influenced by both the amount of moisture in the arc and the deoxidation reactions. Underwater wet welding consumable development must investigate the effective use of complex chemical reactions associated with oxygen and hydrogen. Changes in hydrogen content has also been related to welding parameters such as polarity, current, voltage, travel, and environmental conditions such as depth and the salt content of the water. A number of mechanistic models have been suggested for these behaviors and research programs must be designed to test and confirm these suggested models.

A central theme to the management of hydrogen is the numerous ways in which time dependence can play a role. The concentration and distribution of diffusible hydrogen in the weld metal and heat affected zone is strongly dependent on the thermal experience. The measurement of diffusible hydrogen involves destructive testing and considerable waiting times. The evaluation of hydrogen damage susceptibility by implant testing also involves long testing times due to the need for low strain rates. The cracking requires hydrogen-induced transport to the crack tip to propagate. New diagnostic methods must be developed to reduce this time dependence.

Temper bead practice has been shown to be a promising technique to reduce the HAZ hardness and hydrogen cracking susceptibility. This practice needs a more analytical base to select temper bead welding parameters. Critical location of the temper beads also require specially trained welders to perform these welds. The use of electro-transport as a means to reduce localized hydrogen concentrations by redistribution must be evaluated. With indications that underwater wet weld responses to the electro-transport treatment, a low temperature substitution for postweld heat treatment, the practice must be developed and established.

V. Underwater Welding Practice Of Higher Strength Structural Steels

The underwater wet welding of higher carbon equivalent steels requires the application of the above metallurgical concepts. A practic to wet weld steels with carbon equivalents higher than 0.40% has been developed and demonstrated as a practice. This practice was first used because of a failure of an Amoco U.K. North Sea Platform. The failure was the result of ship impact on a brace of the platform. An inspection of the platform revealed that a diagonal brace connecting Leg B3, at a point 26 feet above water to Leg E3, at a point 36 below water (Figure 40) had a severed weld which had connected the brace to the E3 leg node (Figure 41). The failure was the result of ship impact on the brace. Initial assessment concluded that the damage did not affect the integrity of the platform and no emergency measures were required. However, in order to prevent further degradation of the damaged member from wave action, the brace was removed. An analysis was conducted which showed that the structure could adequately withstand the design conditions with the damaged brace removed. However, it was concluded that in due course, the brace should be replaced to ensure satisfactory long term fatigue performance of the structure. It was also felt that the brace replacement would provide alternative load paths in the event of damage to the structure at other locations.

It has been established practice in the North Sea to use dry hyperbaric welding where major structural underwater repair of components is required. Underwater wet welding techniques had been successful in the Gulf of Mexico and other areas of the world where lower strength steel such as A36 with carbon equivalents lower than 0.40% were used. The construction of offshore structures in depths greater than 100 meters or in the hostile environments of high wave action, such as the North Sea, required greater load carrying capacity which could only be satisfied with large steel section or with higher strength steels. Amoco Corporation believed that a wet welding procedure using the temper bead techniques described earlier could be developed to meet the requirements of underwater wet welding of higher strength steels. Such a wet welding repair would also require a new brace with scalloped sleeves as shown in Figure 42. After long term testing with Global Divers of Lafayette, Louisiana the project was approved.

Amoco kept the Certifying Authority, Lloyd's REgister, appraised of the development program and, when presented with the test results, the Authority accepted the proposal to employ wet welding for the replacement of the brace. This approval was contingent on having the selected welding contractor successfully qualify both the weld procedure and the diver-welders using the proposed temper bead technique for wet welding. Comex of Aberdeen and Marseille was selected to undertake the work on the basis of low bid, technical competence, and their positive approach to adoption of the required technology.

Welding procedure qualification tests were conducted by Comex at Ifremer Research Institute facilities in Brest, France. The welding procedures were qualified on groove and fillet welds using temper bead technique. The qualification tests were conducted on the actual stub material that had been left over from the failure analysis. The final carbon equivalent of the stube materials was found to be around 0.42%. , so testing was conducted with Grad 50D material that had a 0.42% carbon equivalent. The welding procedure qualification tests included tensile tests, bend tests and metallurgical cross sections to insure not HAZ crackng and low hardnesses. Charpy impact testing was also conducted on the weld metal and the heat affected zone to adhere to normal UK requirements for surface or undewater dry welds. The impact tests values for the weld metal averaged 40 ft-lbs, and the HAZ average about 50 ft-lbs. The wet welding electrode chosen for this repair was provided by Global Divers.

Following the qualification of the procedures and 12 welder/divers, Comex mobilized to undertake the repair on July 26, 1990. Detailed measurements for fit up were made with the sleeve followed by five days of underwater welding. Wet magnetic particle inspection was then used to confirm the required quality of the weld before the vessel was demobilized. An additional inspection was conducted in January 1991 to ensure that delayed cracking had not occurred. Recent inspections have not revealed problems with this repair.

Conclusions (Section V)

Although wet welding had been previously used in the North Sea for non-structural items, this was the first time it had been used for major sructural components. The short time required to complete the repair and the successful demonstsration of the technology confirms that wet welding can now be economiclly utilized in the North Sea and throughout the world for major structual repairs. The use of the temper bead technique also allows for hardness lmitations to be speicified on any wet welding repair. Previously, wet weld repairs on steels with low carbon equivalents have been allowed to remain the service with hardnesses greater than Vikcers 400. this temper bead technique now provides a way for specifying maximum lmits on the hardness of the HAZ on all wet weld repairs, including high carbon equivalent steels.

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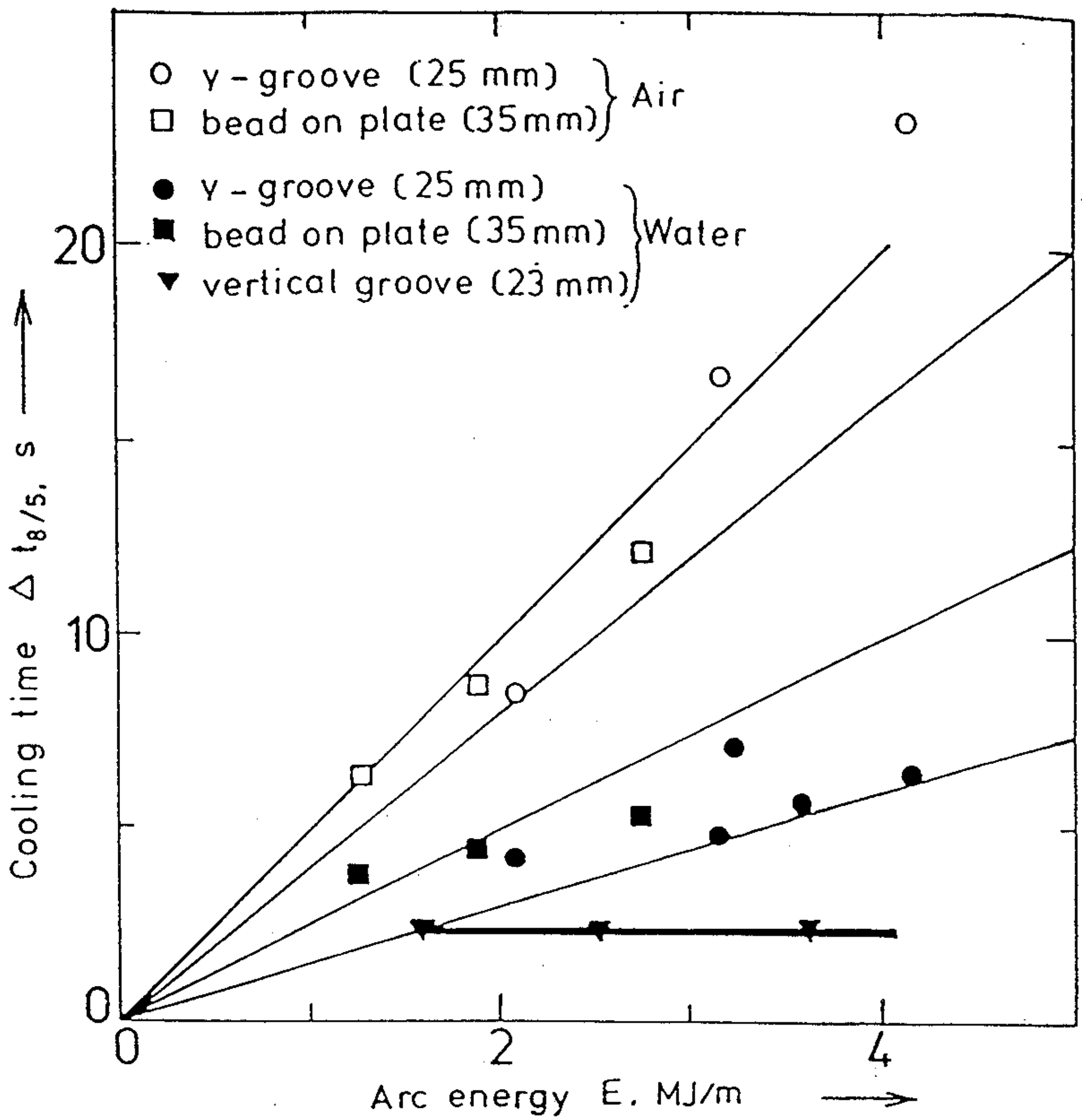

Figure l. Cooling time as a function of arc energy for surface and underwater welding (2).

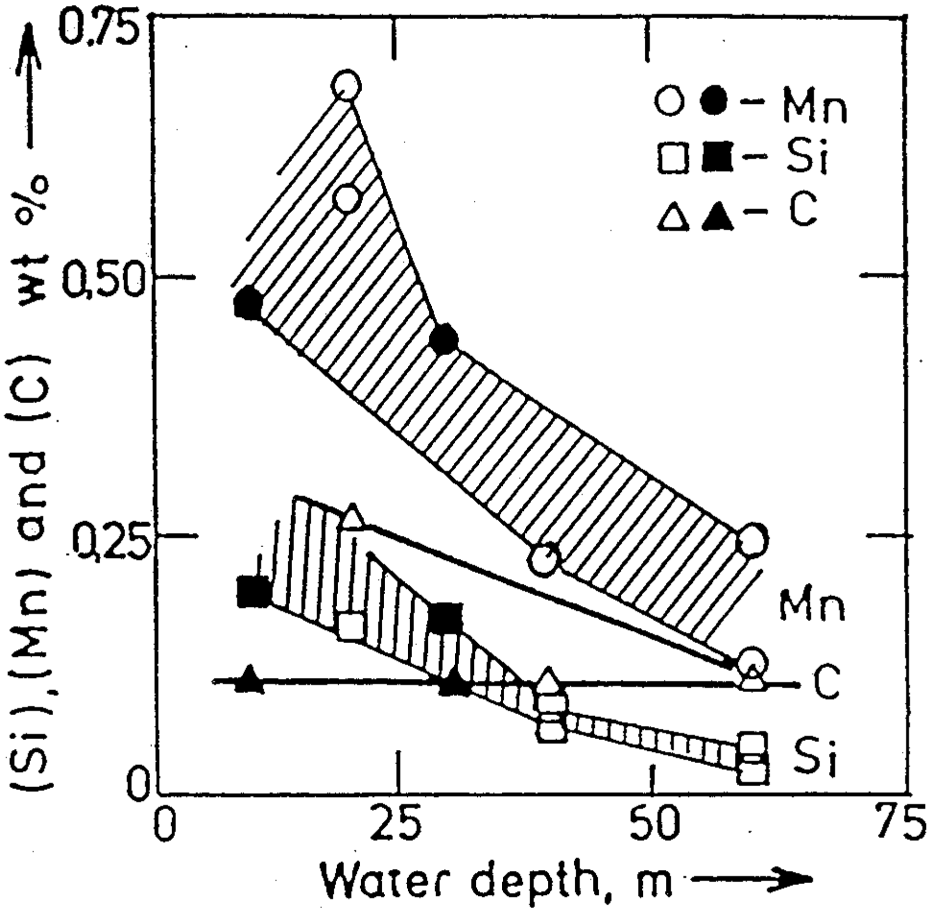

Figure 2. Alloying element variation in underwater wet weld as a function of depth (2,39,51).

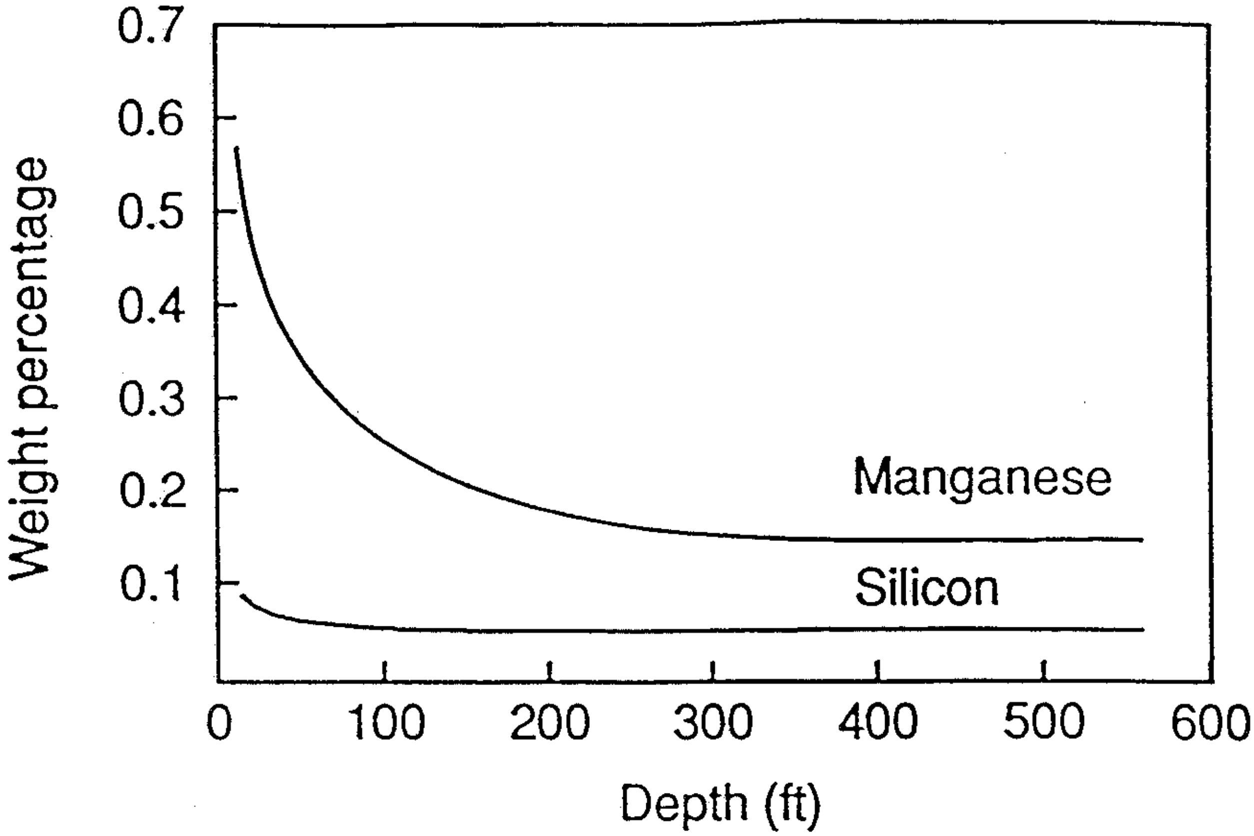

Figure 3. Underwater wet weld metal manganese and silicon as a function of depth (23,53).

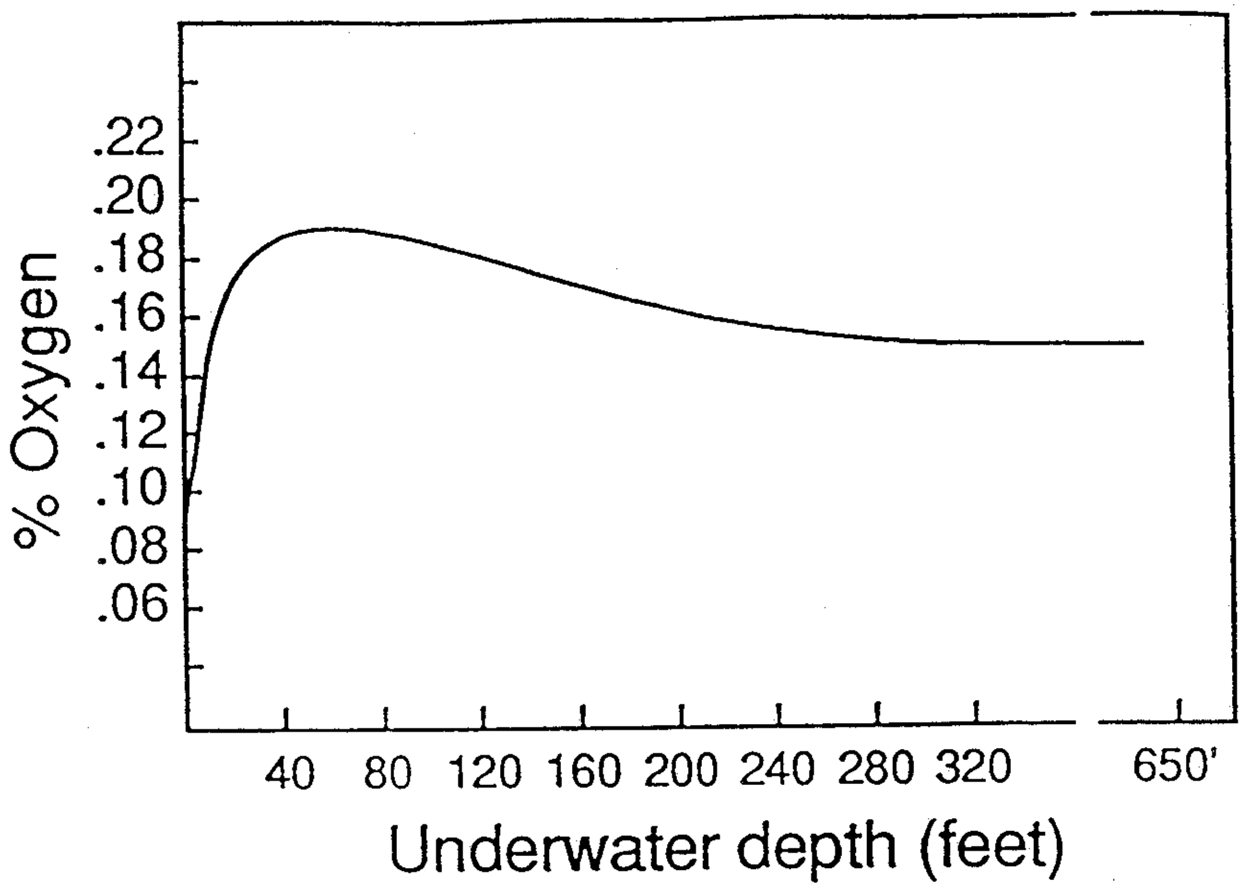

Figure 4. Underwater wet weld metal oxygen as a function of depth (23,53).

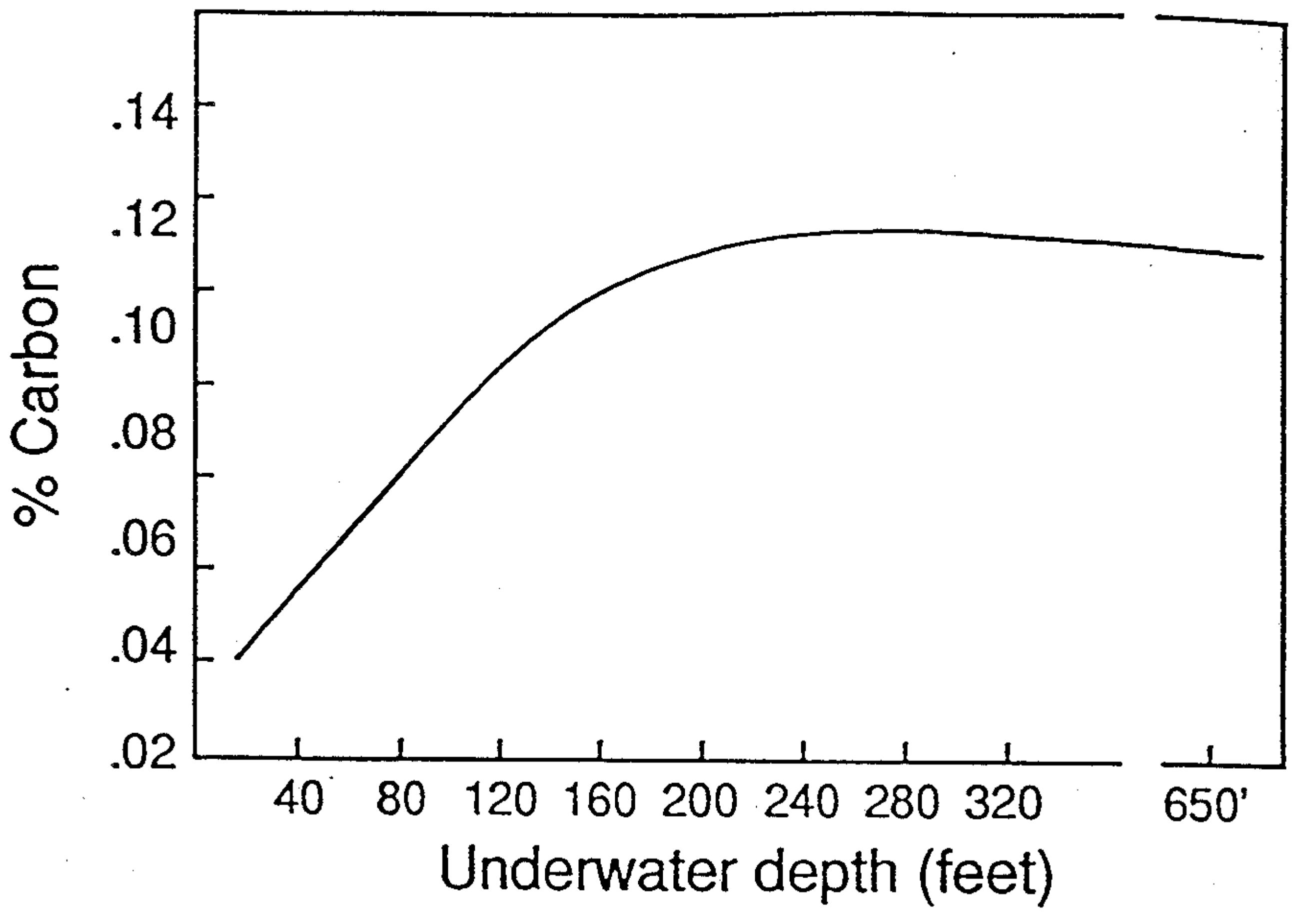

Figure 5. Underwater wet weld metal carbon as a function of depth (23,53).

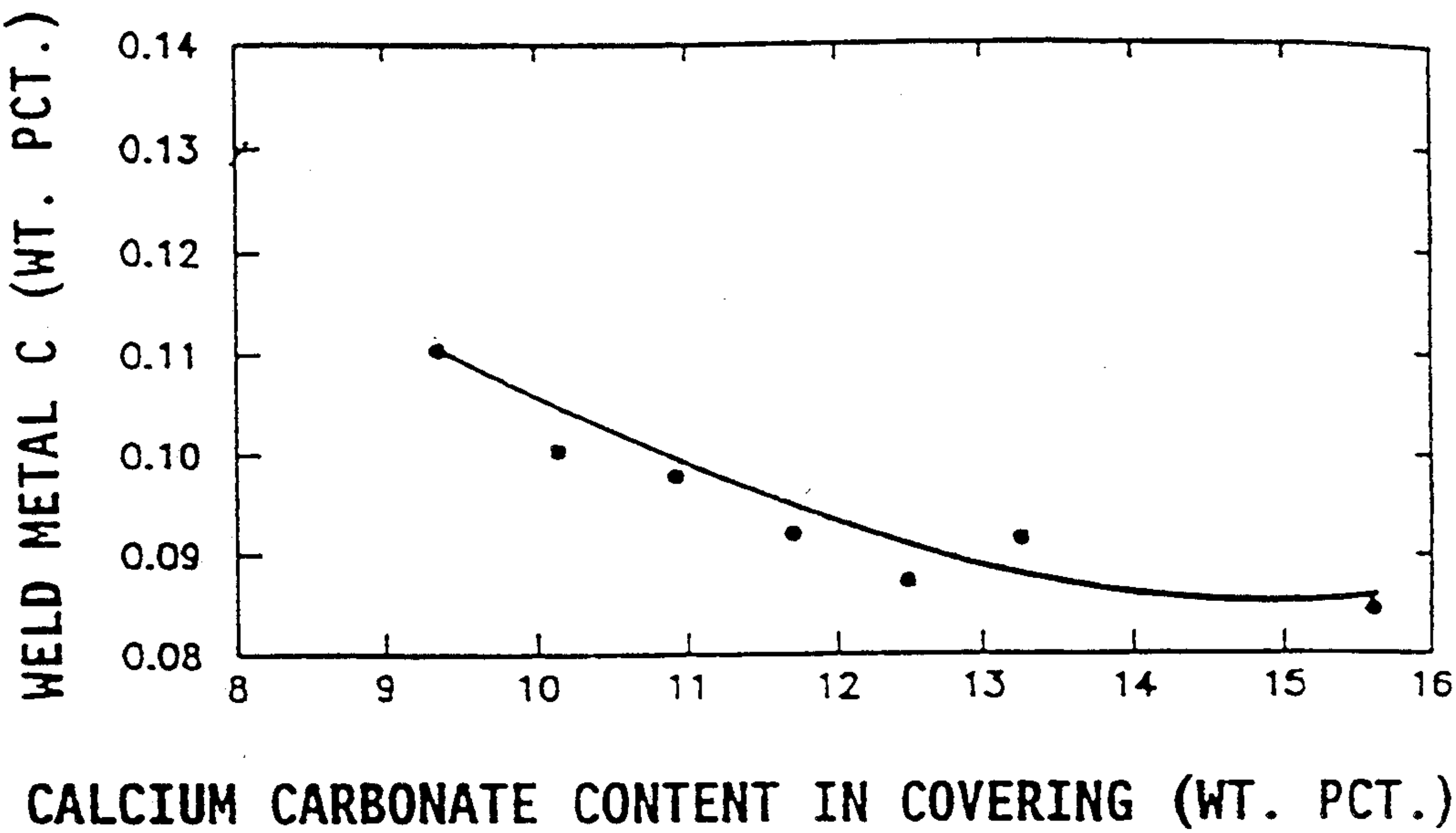

Figure 6. Dependency of weld metal carbon content on calcium carbonate additions in experimental E6013 electrodes (54).

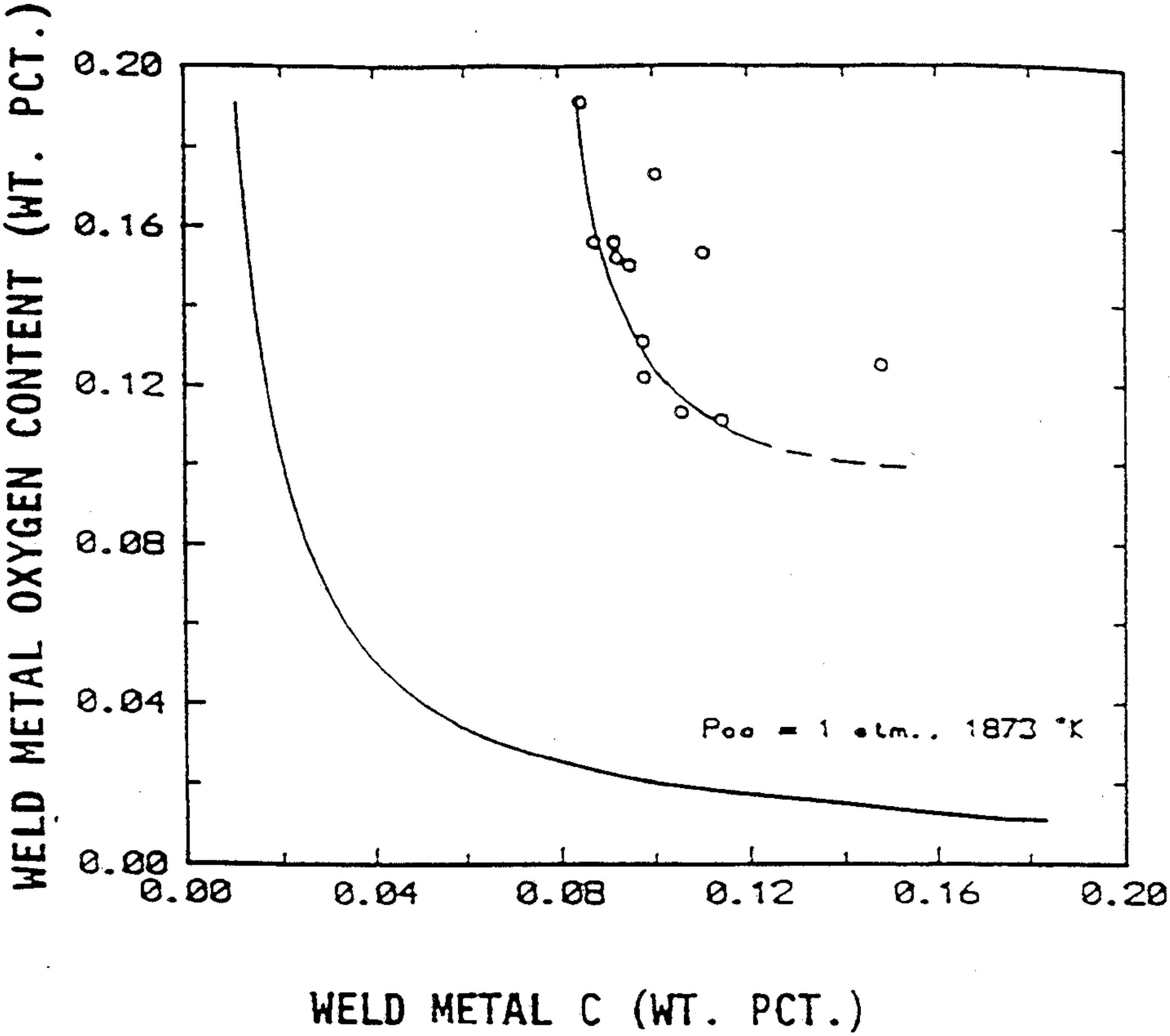

Figure 7. Weld metal oxygen and carbon content. The upper curve represents experimental data and the lower curve corresponds to the C-O equilibrium at 1 atm and 1873°K (54).

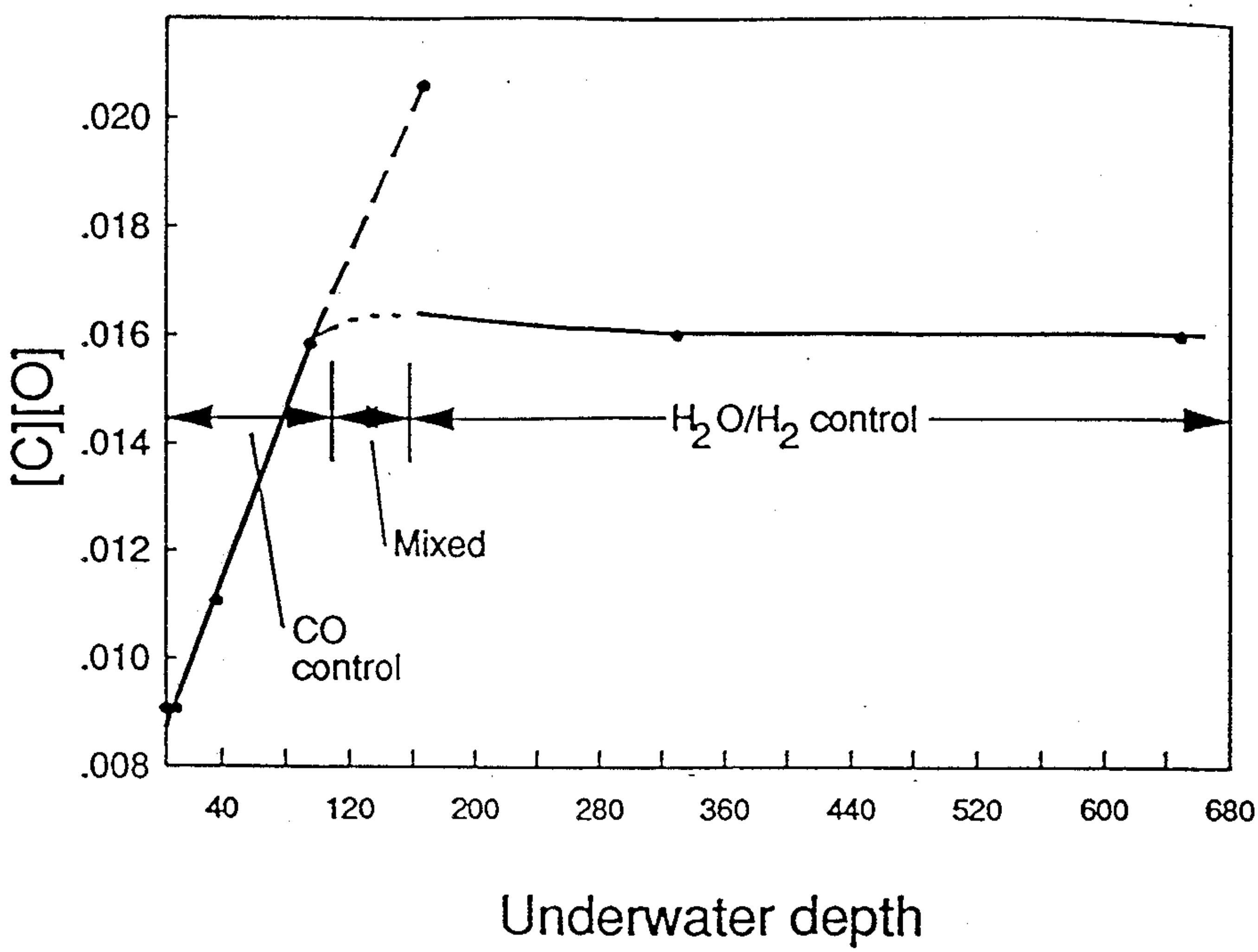

Figure 8. Product of weld metal carbon and oxygen content as a function of underwater depth for weld metal produced with treated E6013 SMA electrode (23,25).

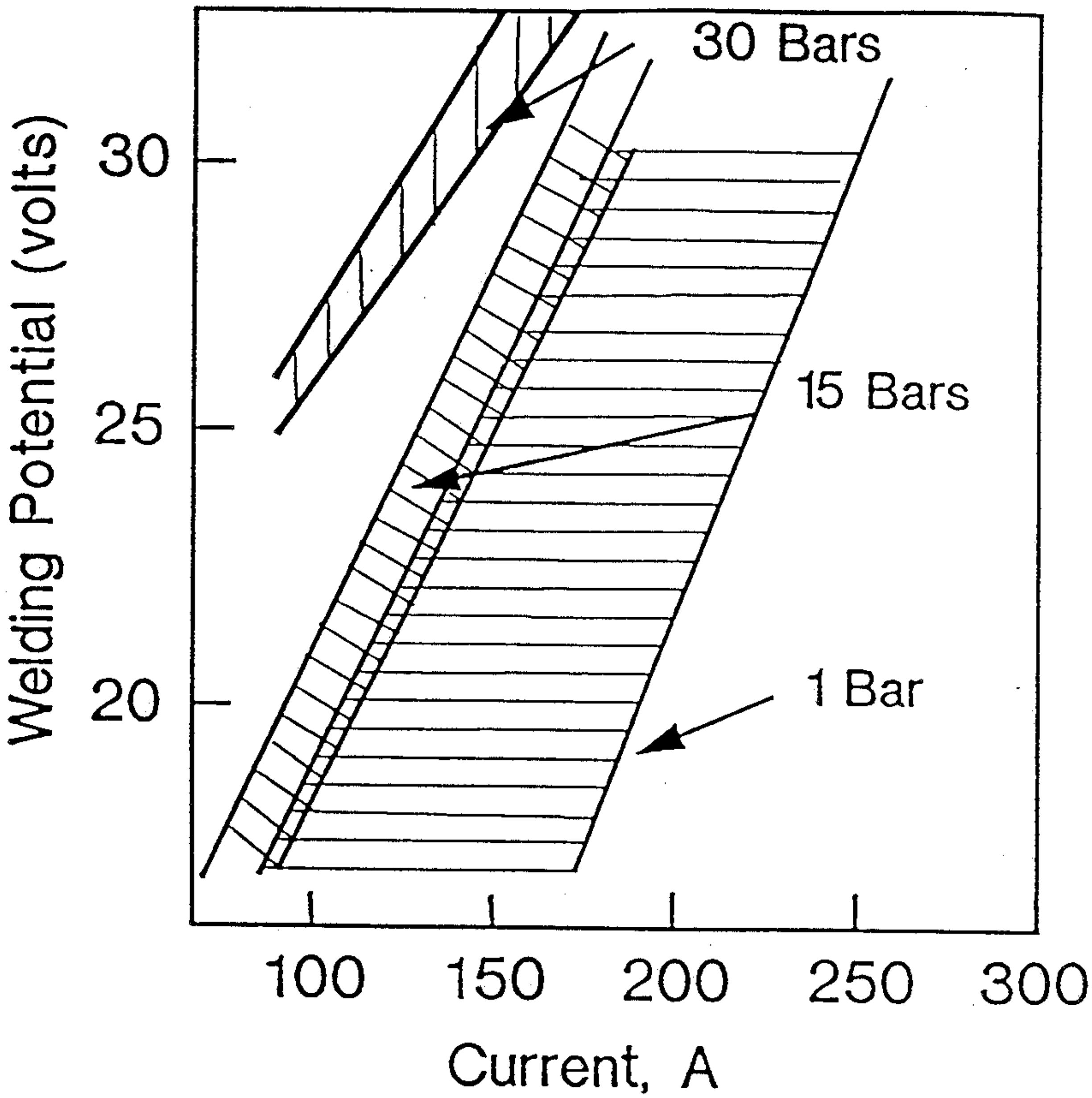

Figure 9. The regions in welding parameter space for successful high-pressure welding as a function of pressure or depth. Note that the acceptable welding parameter space reduces with pressure or depth (55).

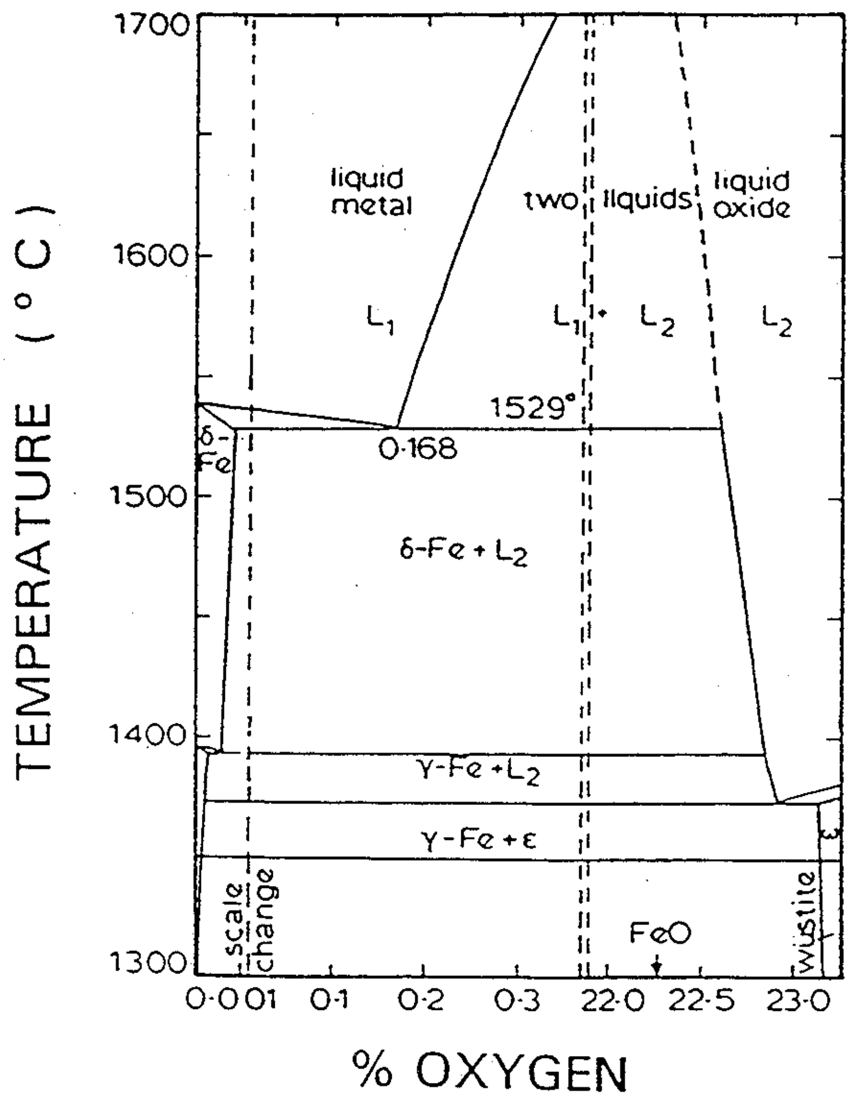

Figure 10. Fe-O equilibrium diagram.

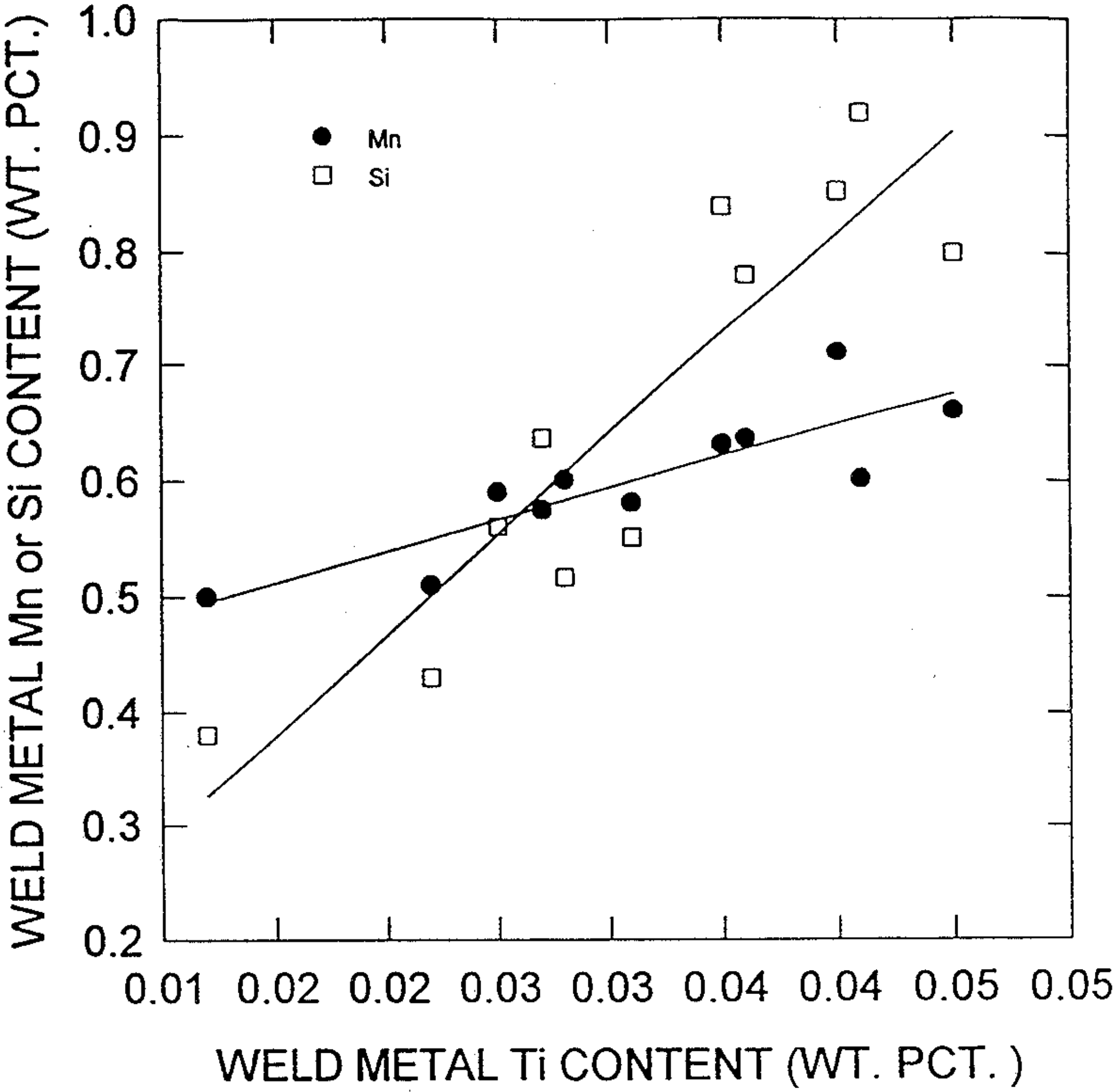

Figure 11. Weld metal manganese and silicon dependency on weld metal titanium content in underwater wet welds (54).

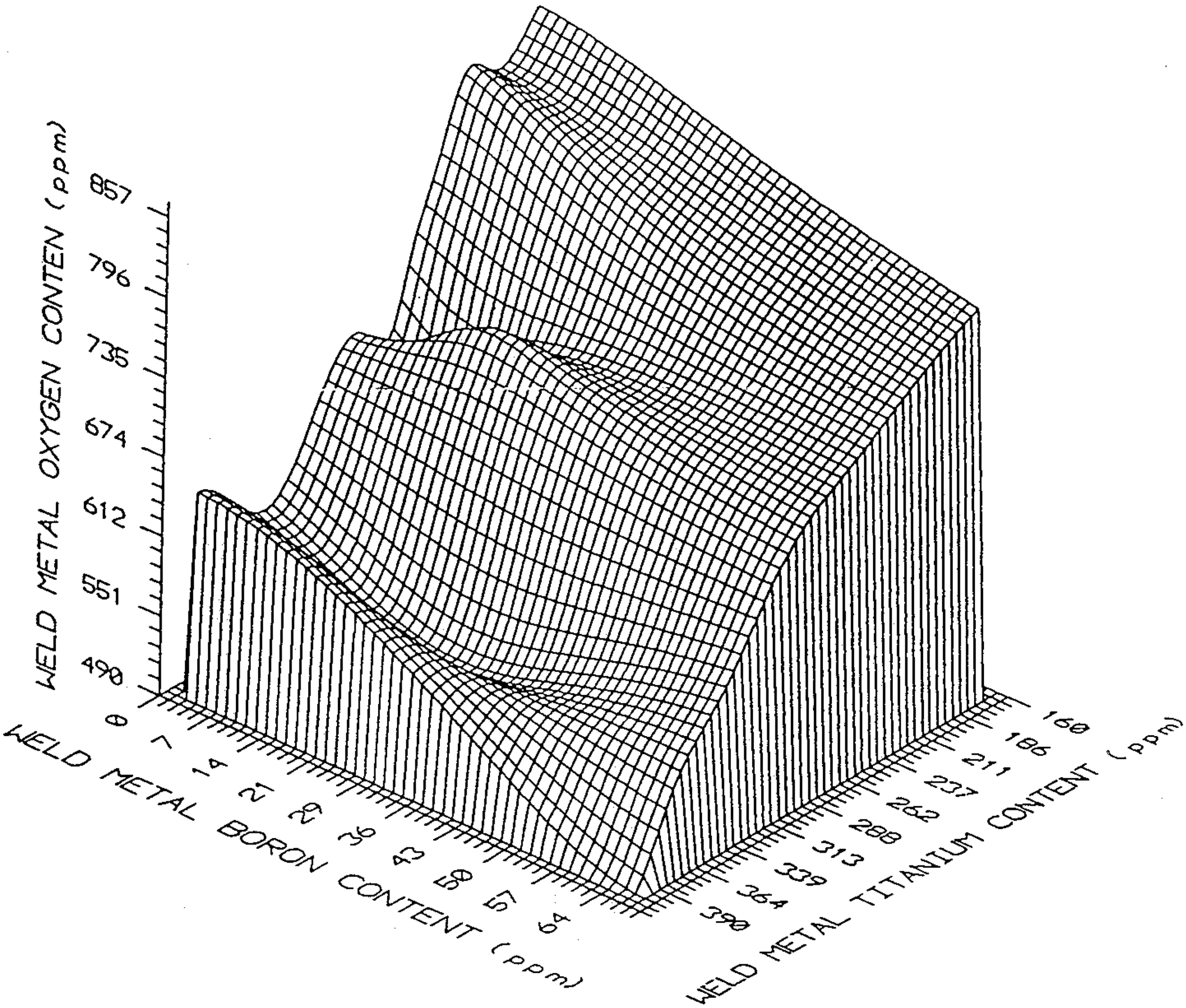

Figure 12. Weld metal oxygen dependency on weld metal titanium and boron content in underwater wet welds (54).

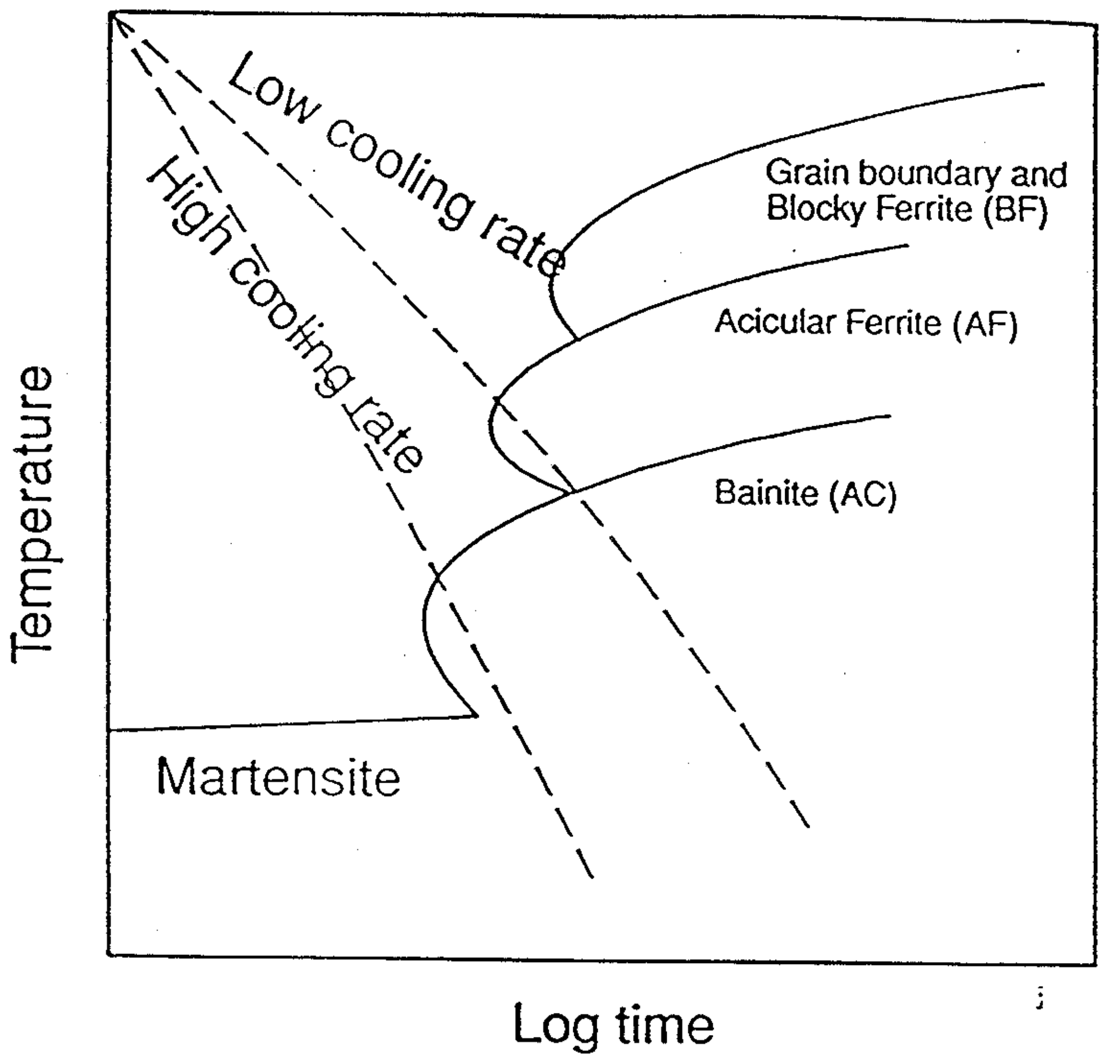

Figure 13. The influence of the cooling rate on the formation of specific weld metal microstructures.

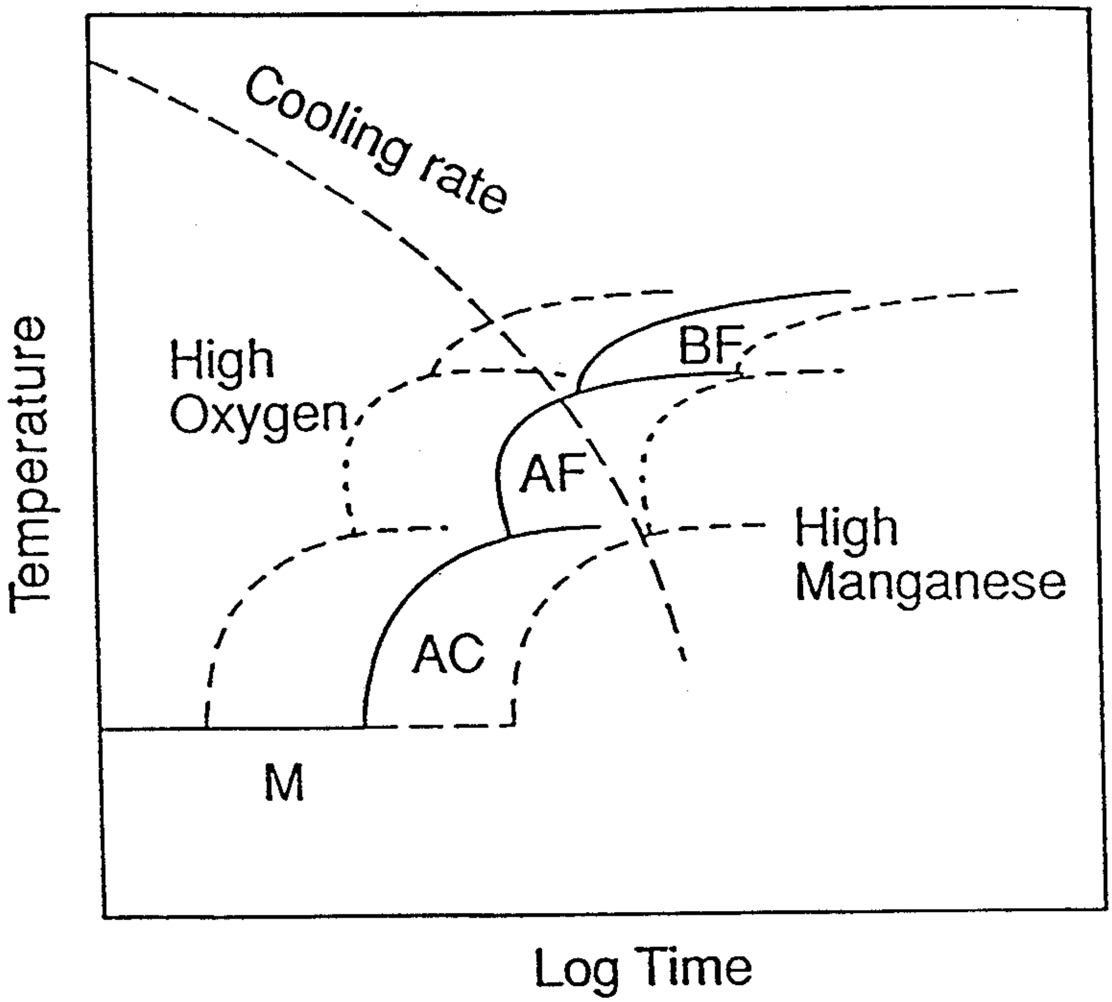

Figure 14. The influence of the weld metal oxygen and manganese contents on the weld metal hardenability.

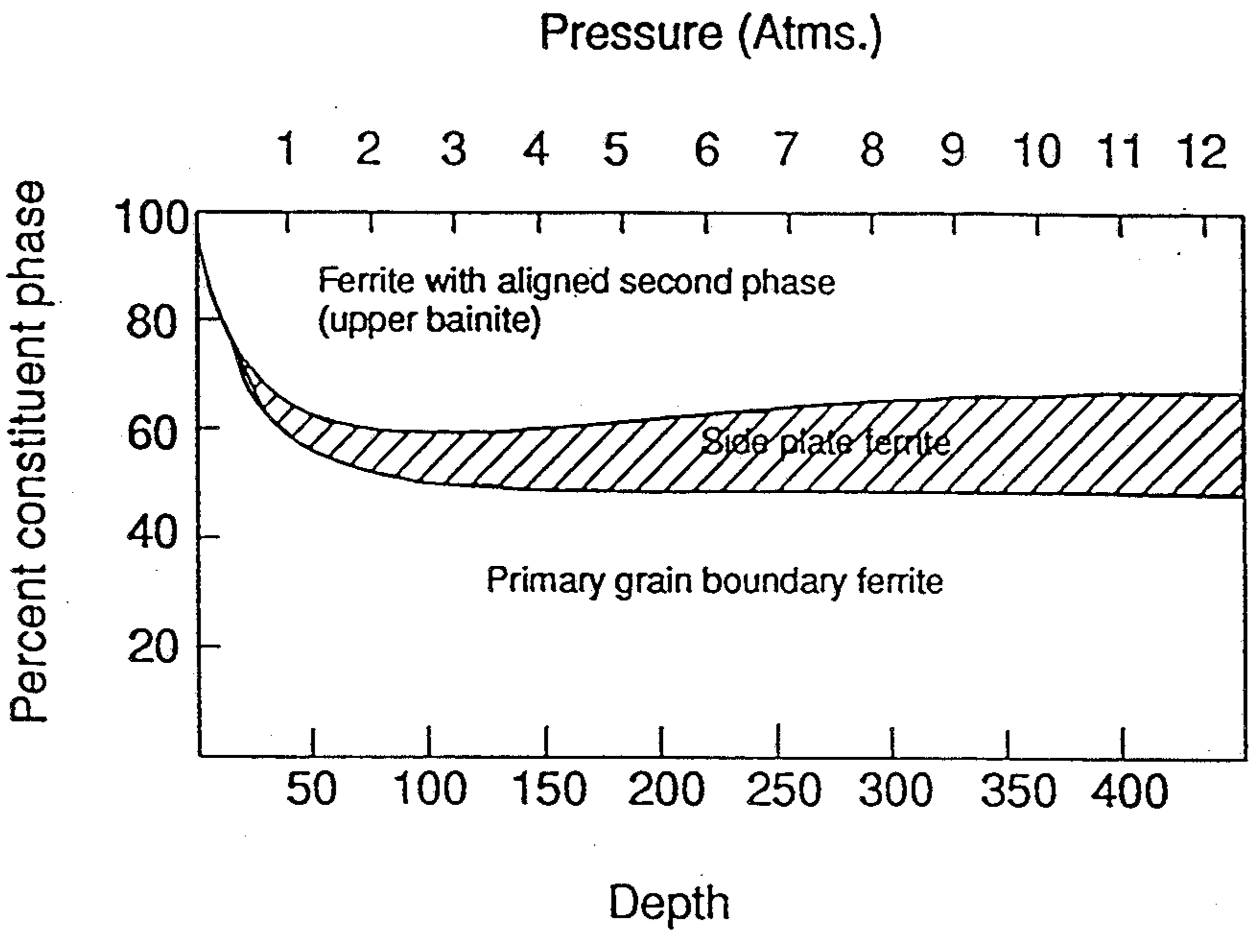

Figure 15. The percentage of the weld metal microstructural constituents for underwater wet welds as a function of water depth (23).

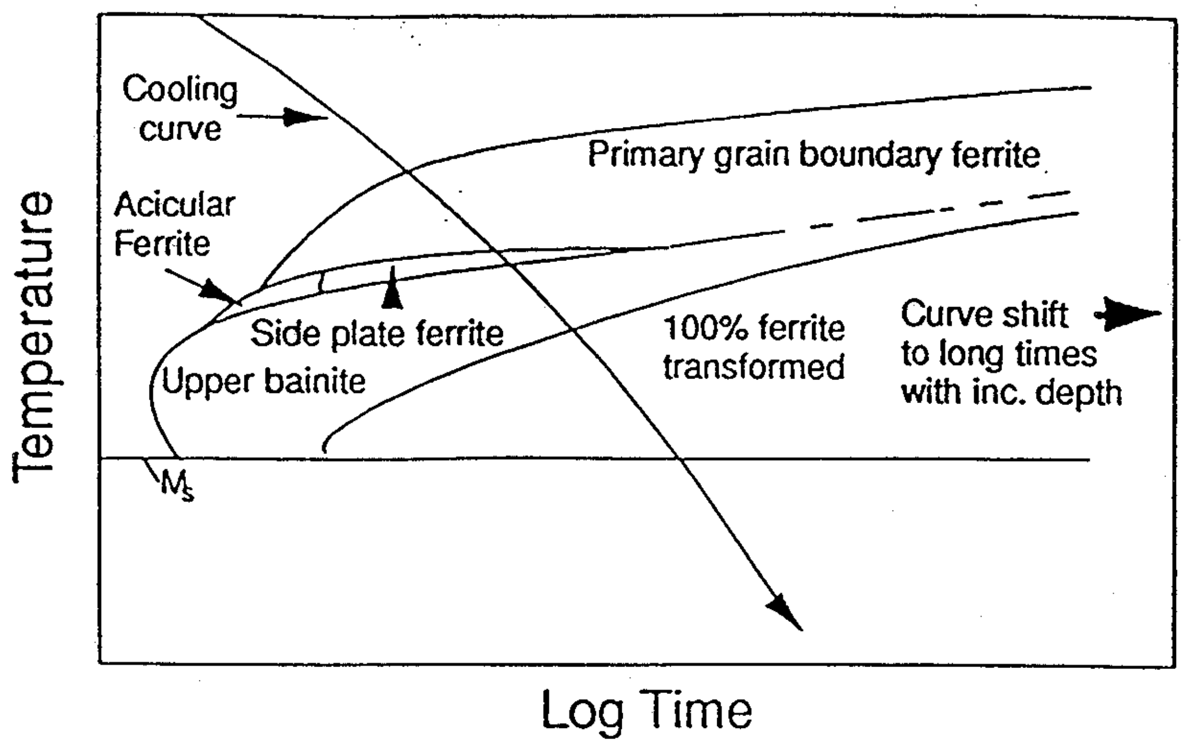

Figure 16. A proposed schematic for the temperature versus log time plot illustrating the nucleation curves for the various weld metal ferrite morphologies in underwater wet welds (23).

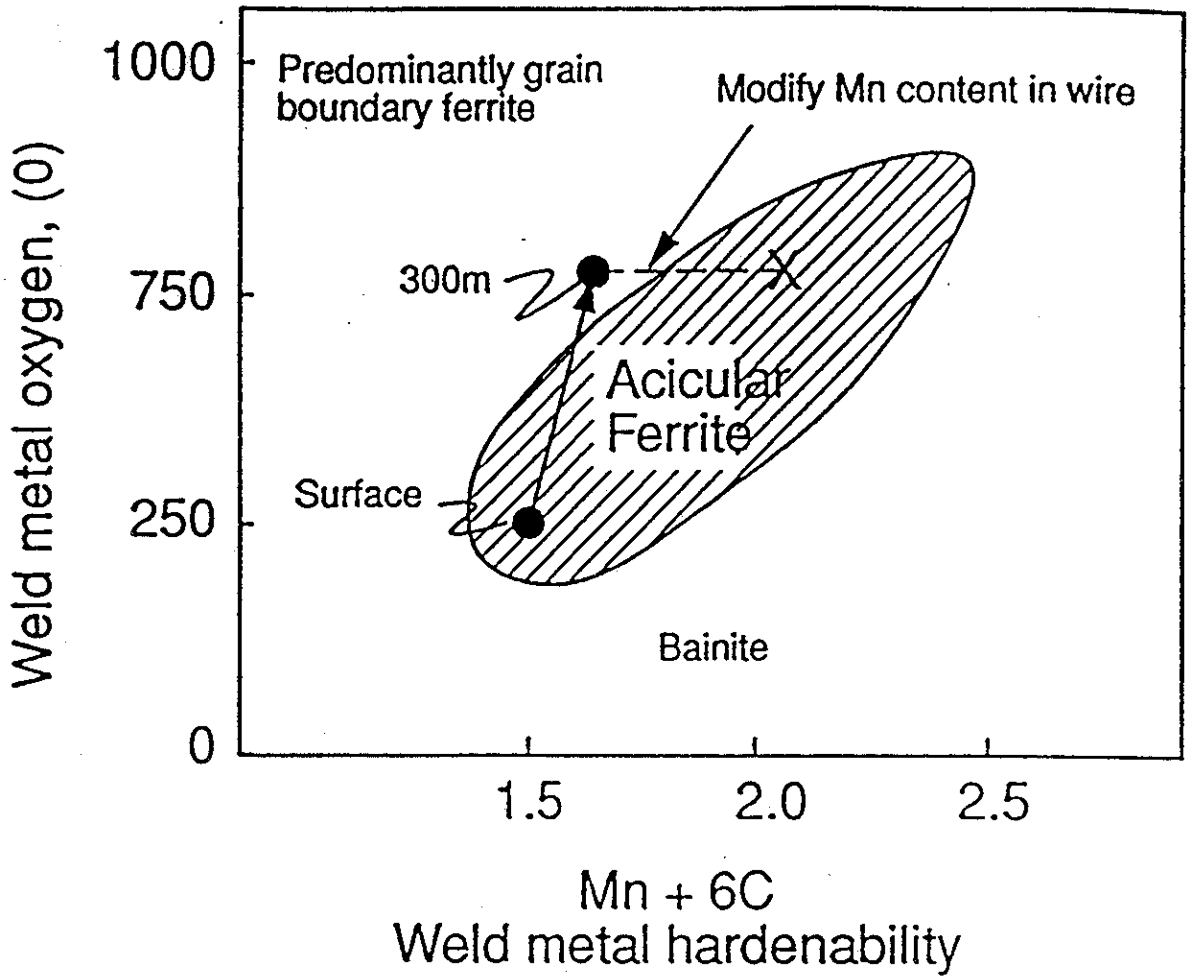

Figure I7. The range of high acicular ferrite content is illustrated on a plot of weld metal oxygen content versus weld metal hardenability. The weld metal composition shift due to changes in depth from the surface to 300 meters is illustrated. The proper manganese modification to bring the weld metal back to an acceptable microstructure is indicated (21).

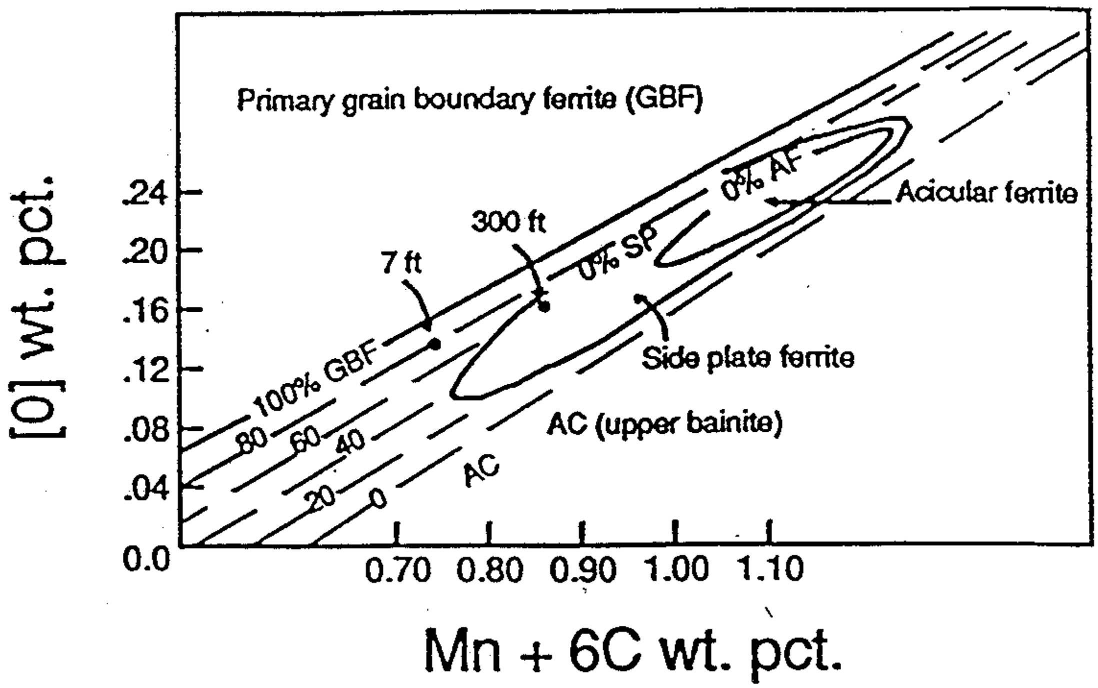

Figure 18. A suggested compositional diagram for the prediction of weld metal microstructure for underwater wet welds (23).

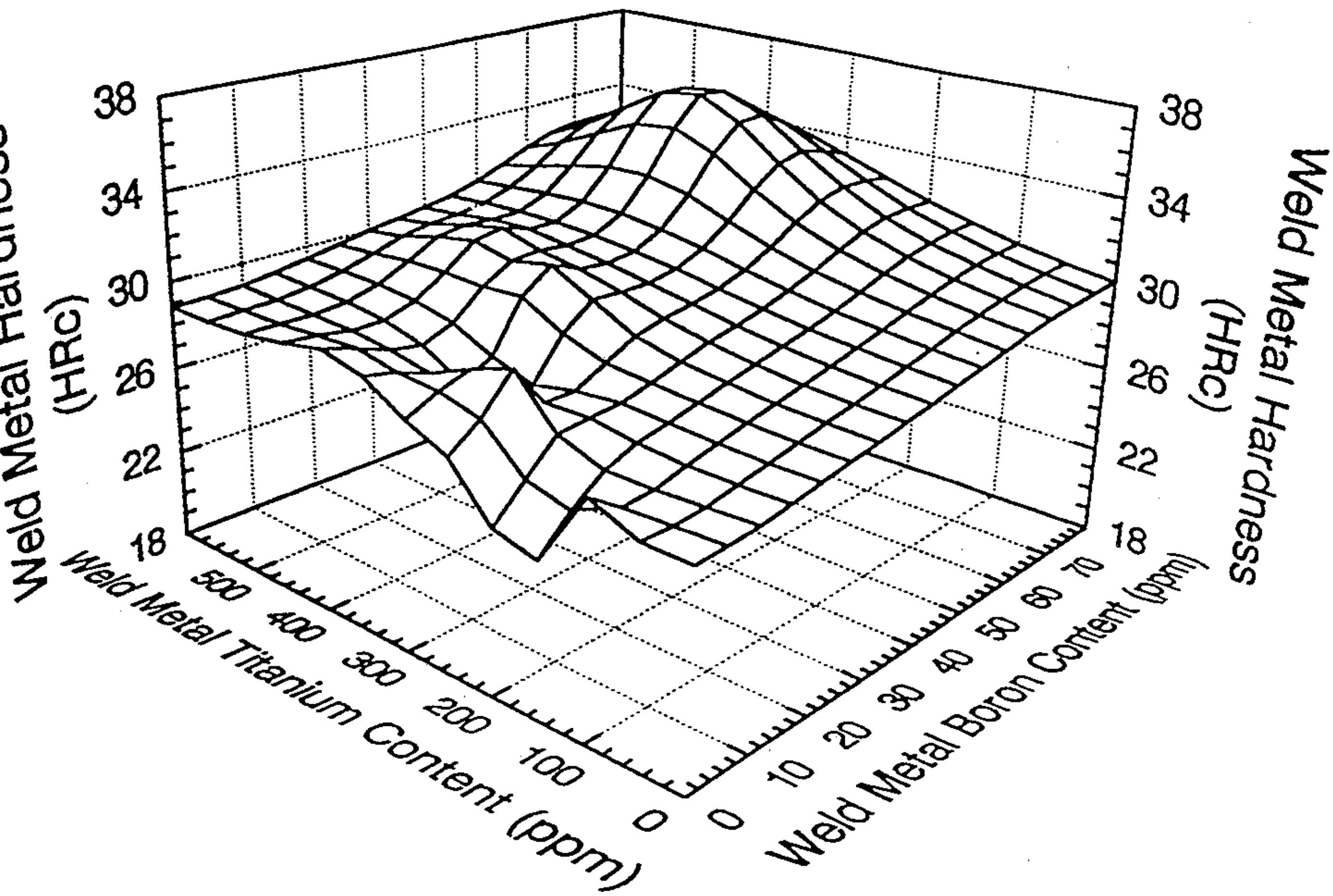

Figure 19. Weld metal hardness dependency on weld metal titanium and boron content in underwater wet welds (54).

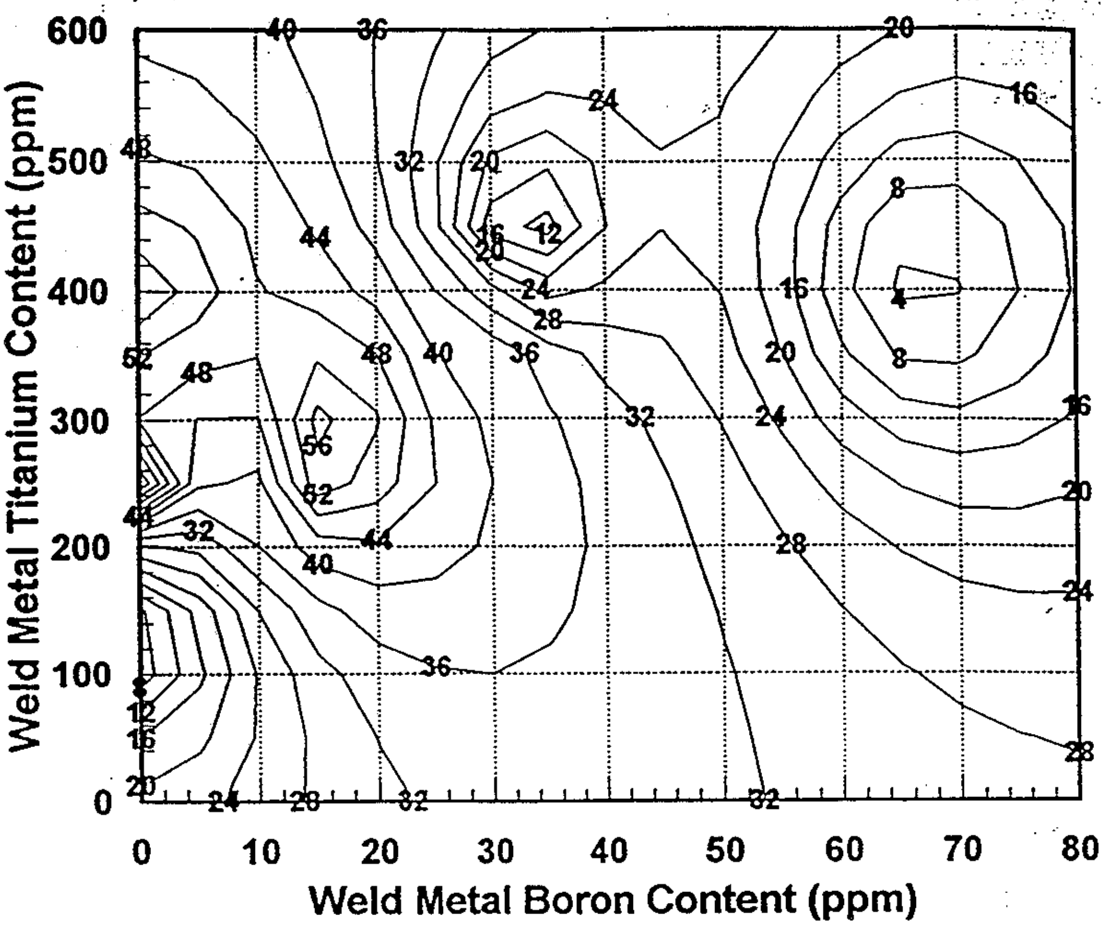

Figure 20. Contour map of acicular ferrite as a function of weld metal titanium and boron content in underwater wet welds (54).

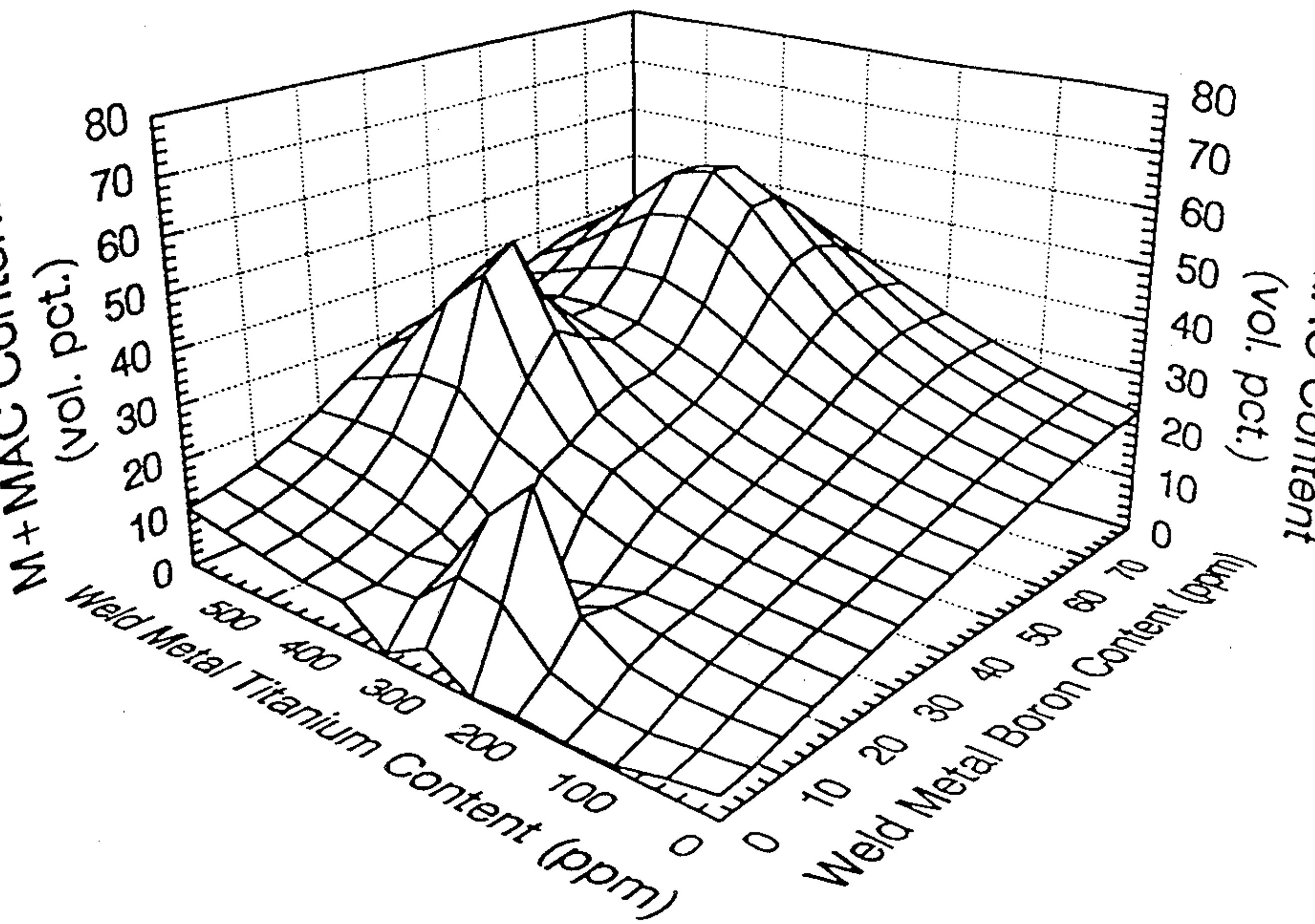

Figure 21. Volume fraction of martensite (M) and microconstituents (MAC) as a function of weld metal titanium and boron content (54).

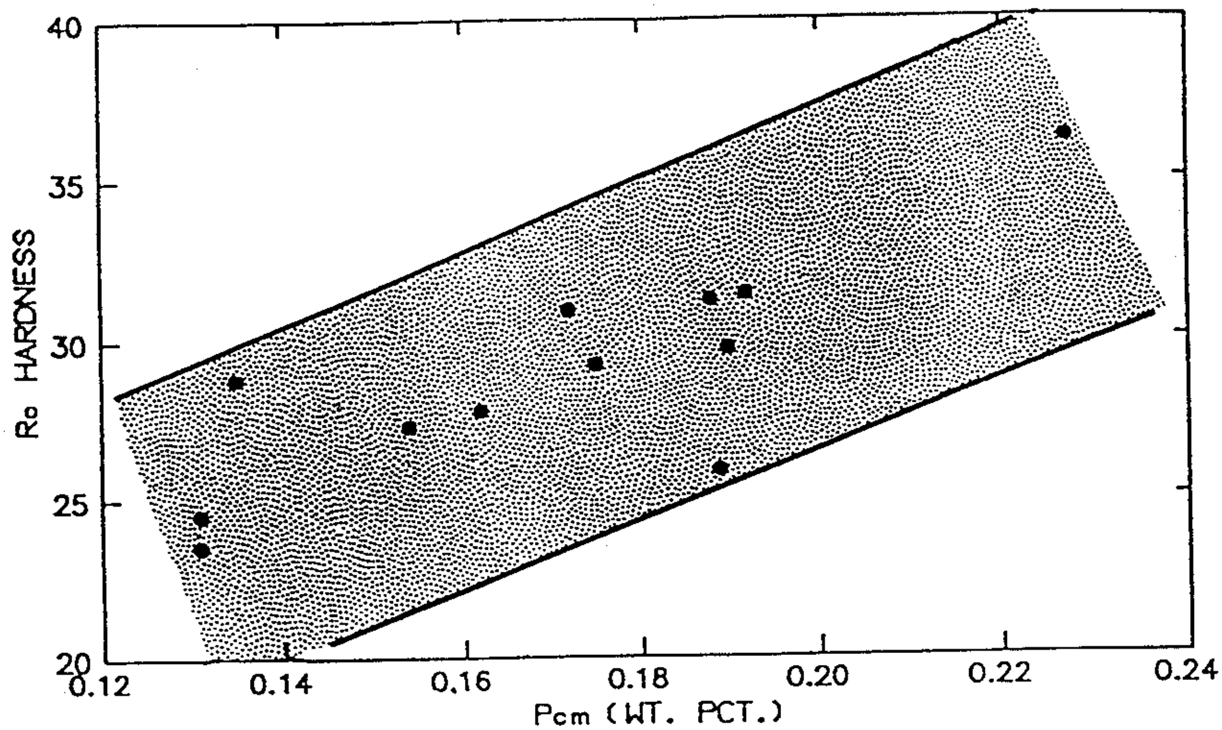

Figure 22. Weld metal hardness of underwater wet welds as a function of P_{cm} (54).

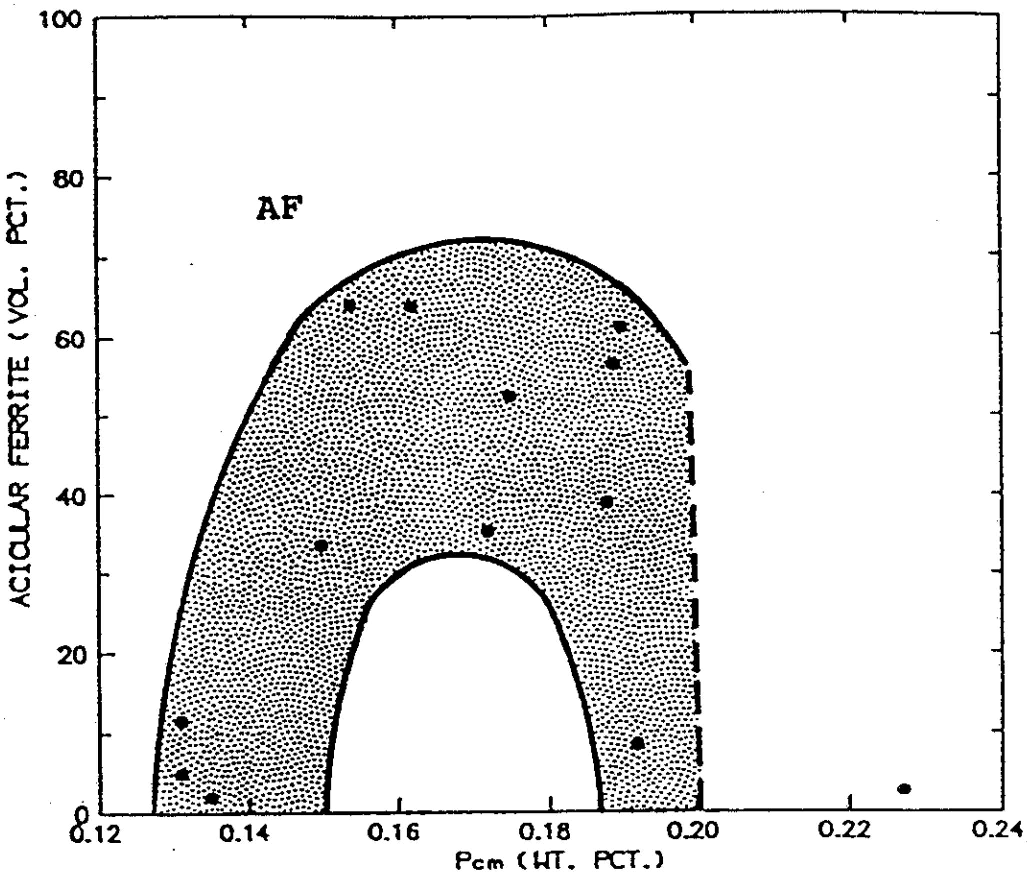

Figure 23. Volume fraction of acicular ferrite in underwater wet welds as a function of P_{cm} (54).

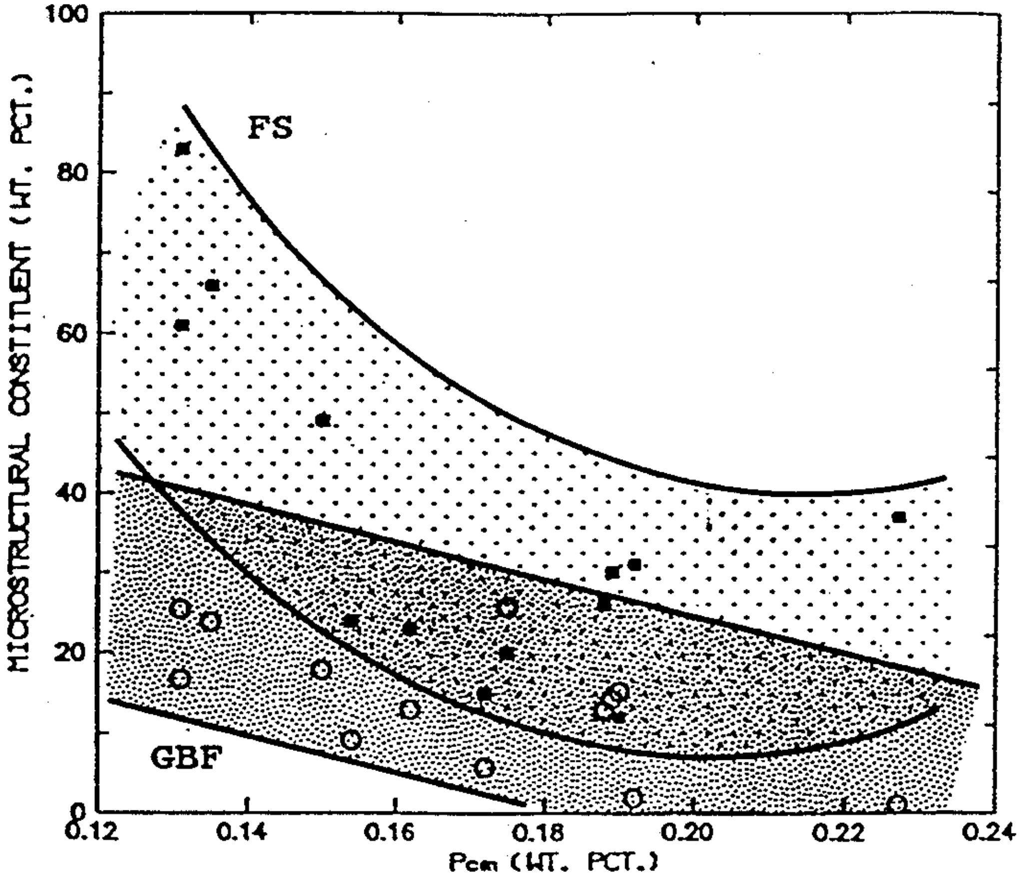

Figure 24. Volume fraction of ferrite with second phase aligned and grain boundary ferrite in underwater wet welds as a function of P_{cm} (54).

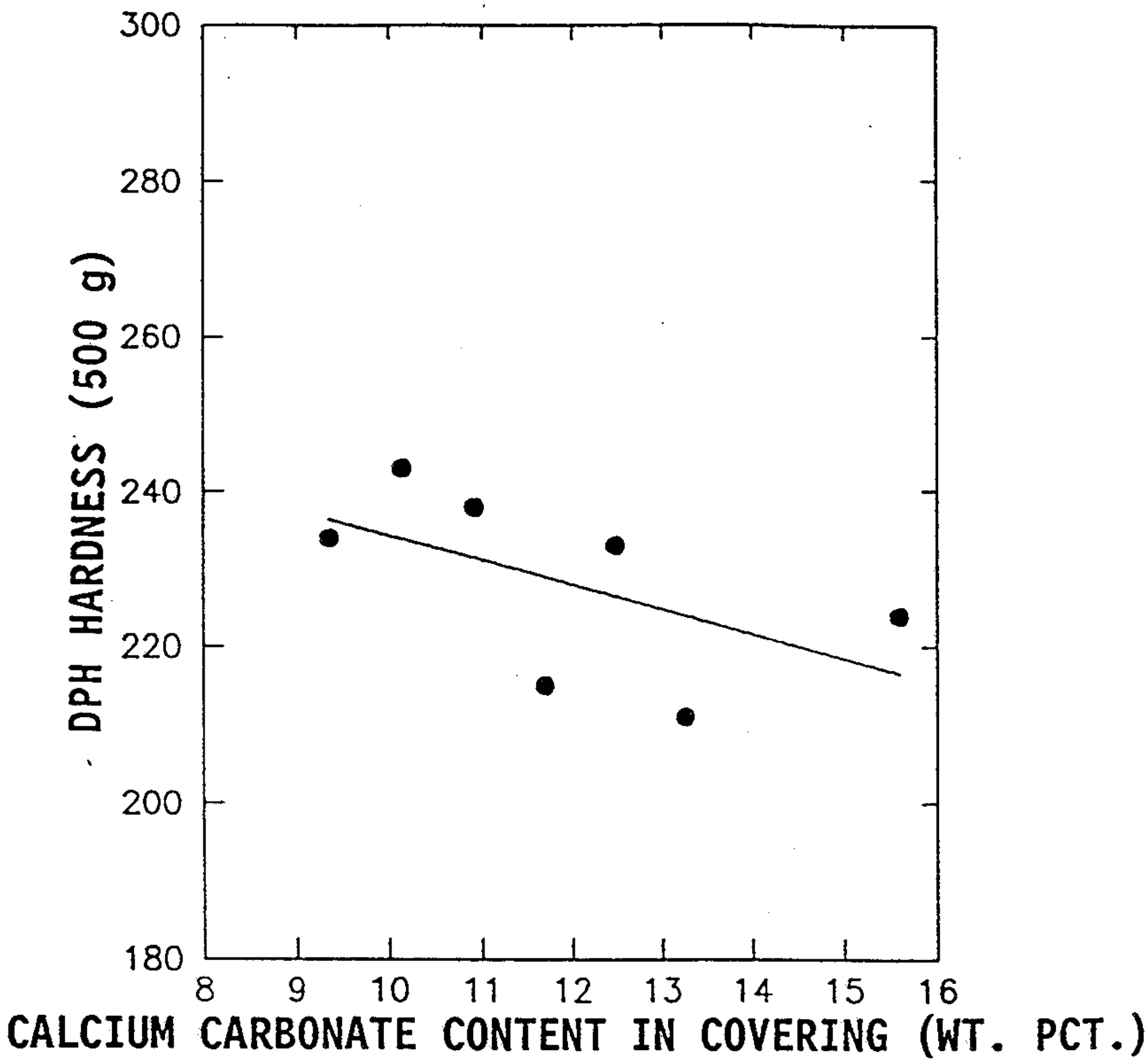

Figure 25. Dependency of weld metal hardness on calcium carbonate additions in underwater wet welds (54).

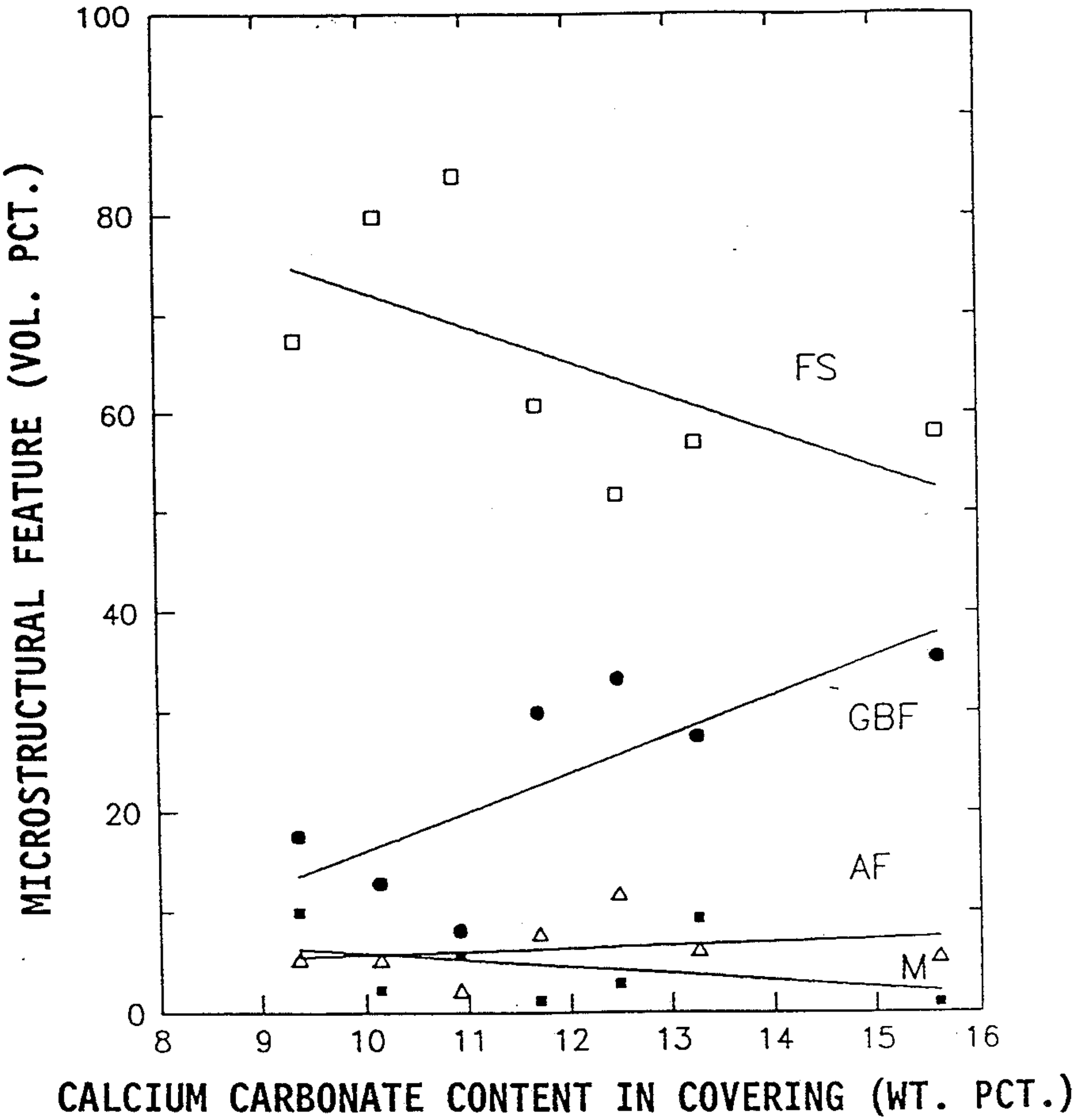

Figure 26. Volume fraction of microstructural constituents in the underwater wet welds as a function of calcium carbonate additions (54).

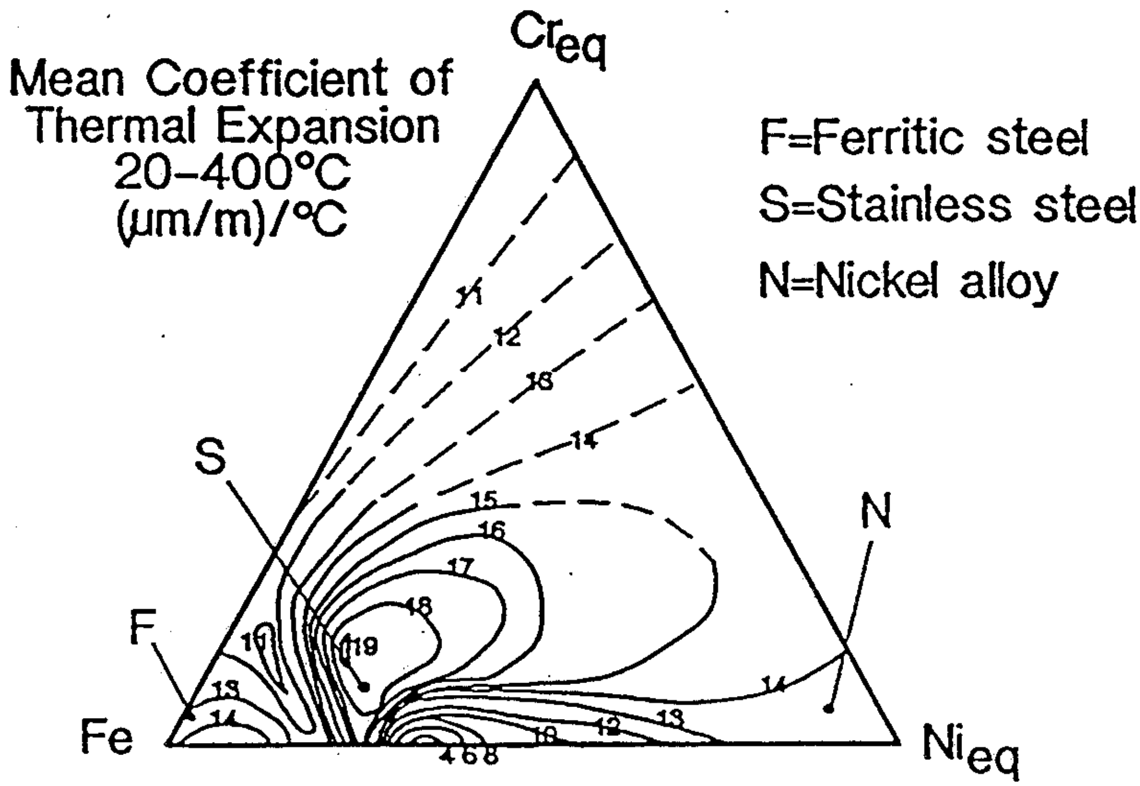

Figure 27. The mean coefficients of thermal expansion for weld metal in the iron-chromium-nickel alloy system (63).

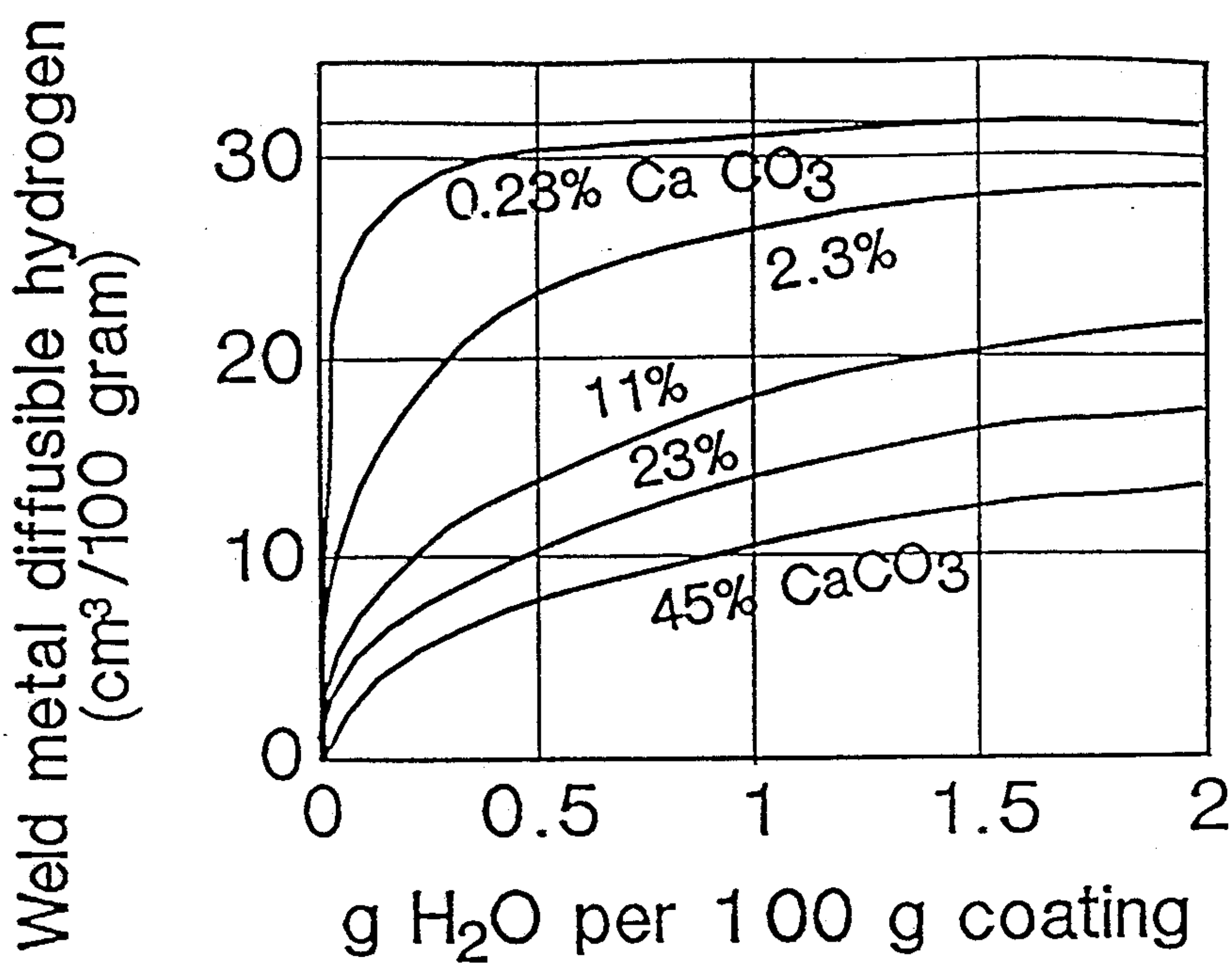

Figure 28. Weld metal diffusible hydrogen content as a function of moisture in the electrode coating for various calcium carbonate contents (65).

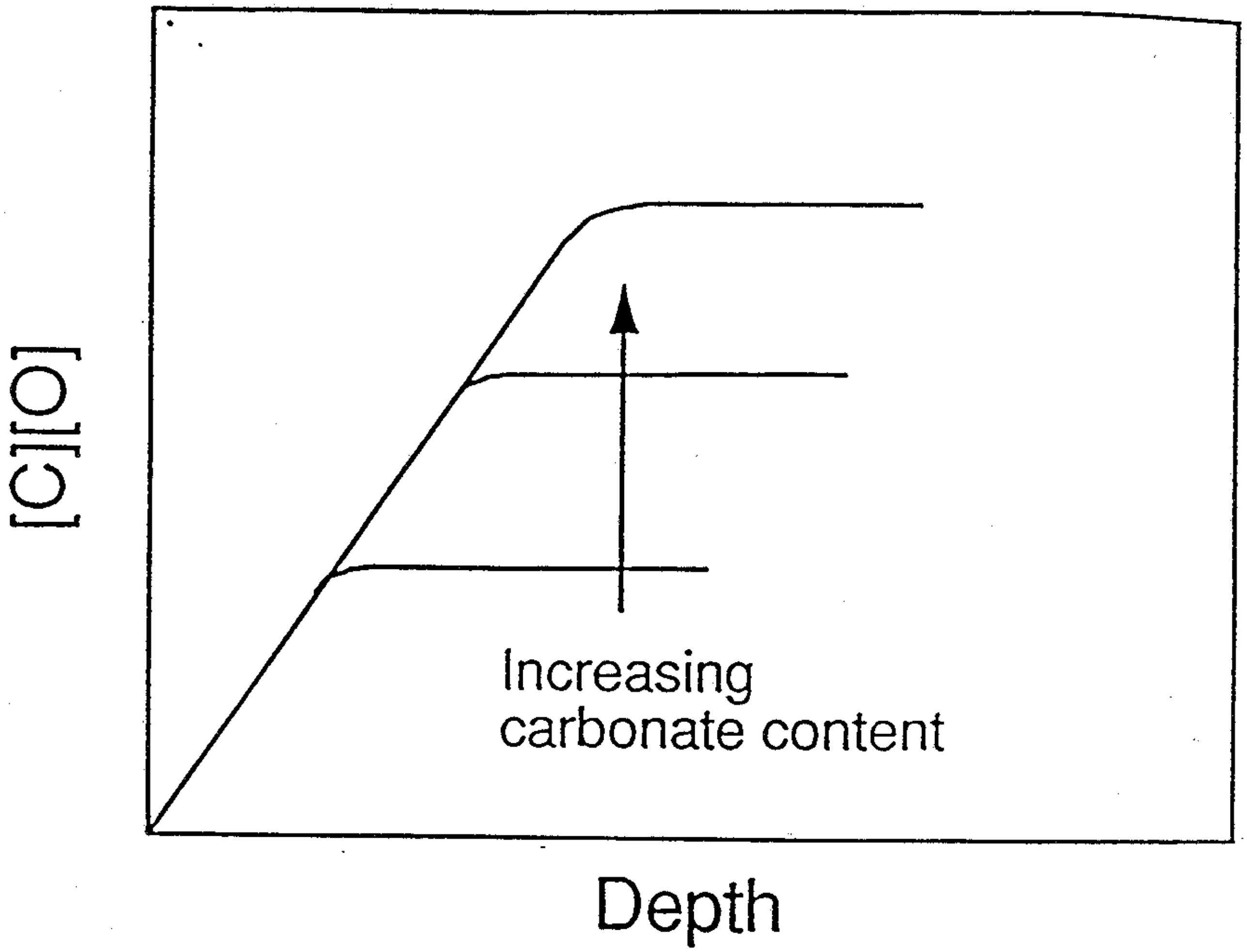

Figure 29. The expected modification of the CO reaction as seen in the [C][O] versus depth plot (Figure 8) with increasing carbonate content in the electrode covering (22).

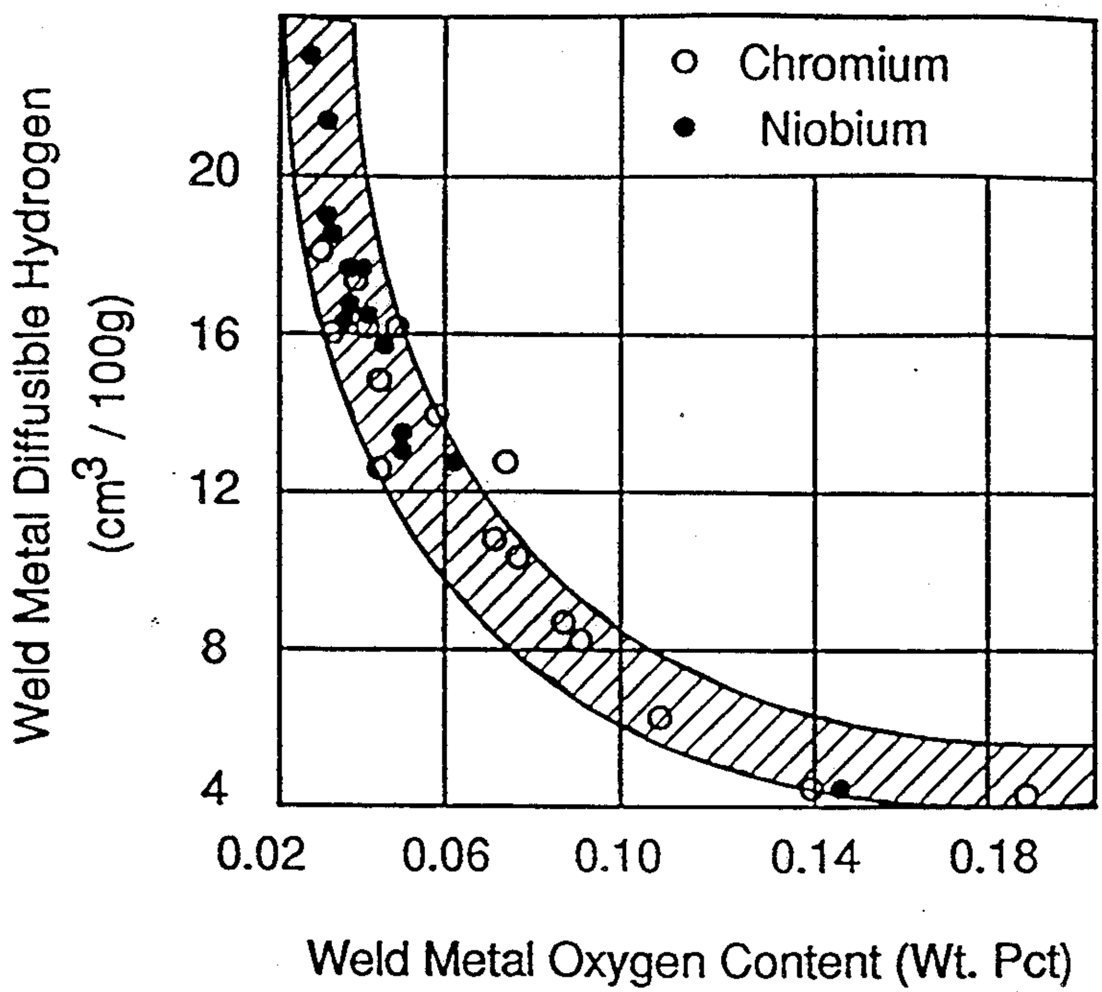

Figure 30. Relationship between the weld metal oxygen and hydrogen contents in welding with electrodes with chromium and niobium in their coatings (65).

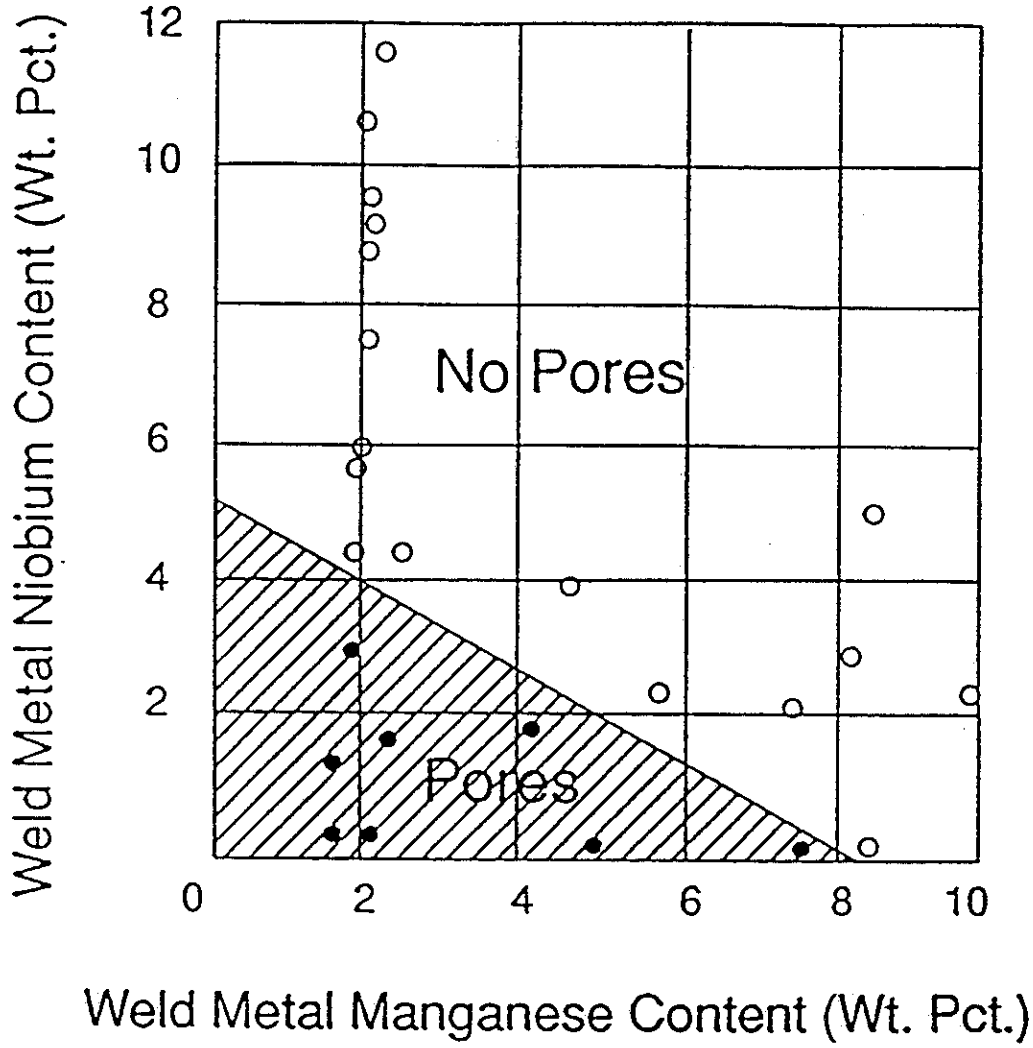

Figure 31. The critical concentration of niobium and manganese preventing the formation of pores in the metal deposited with electrodes containing 10 pct. $CaCo_3$ in the coating (65).

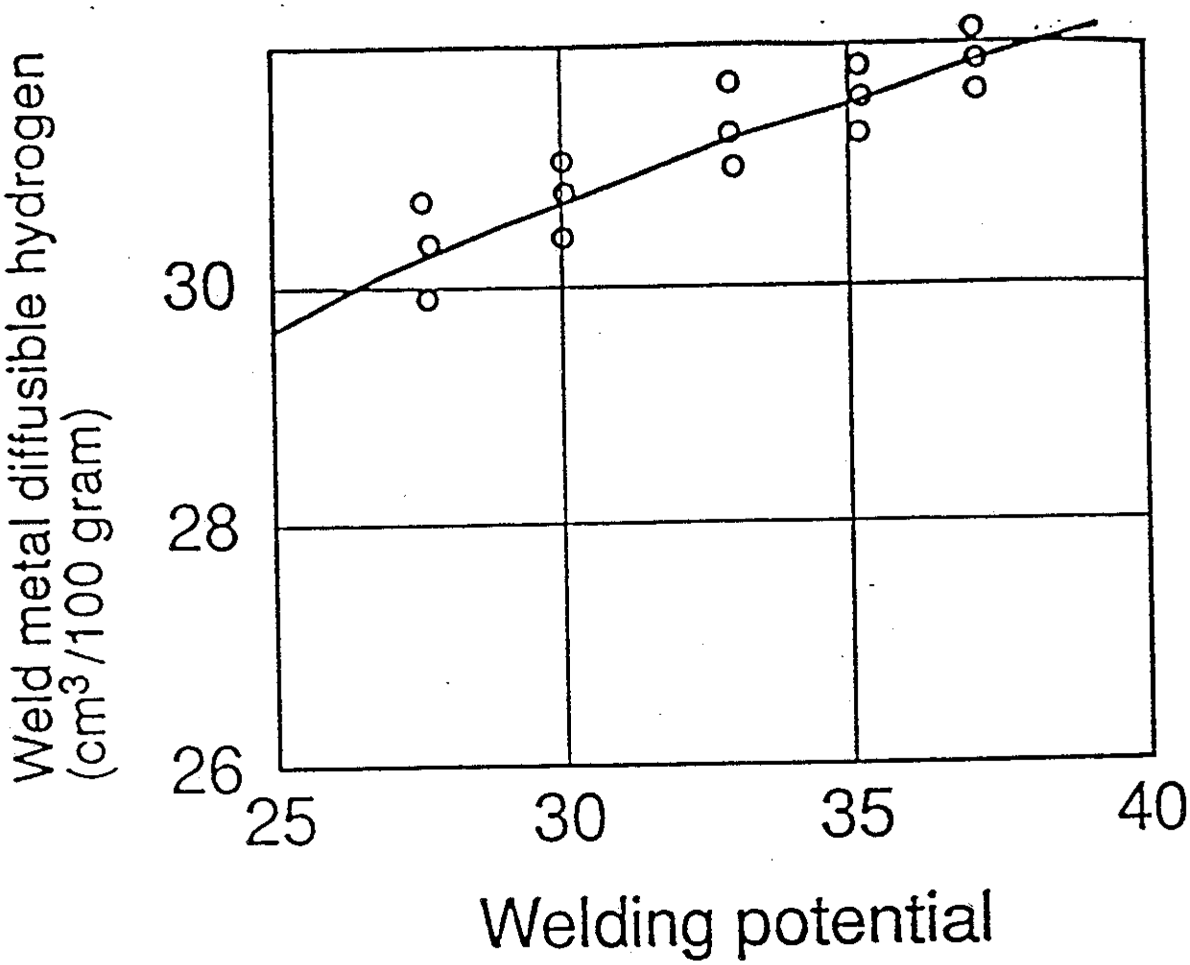

Figure 32. Effect of arc voltage on the hydrogen content of wet underwater weld deposits (70).

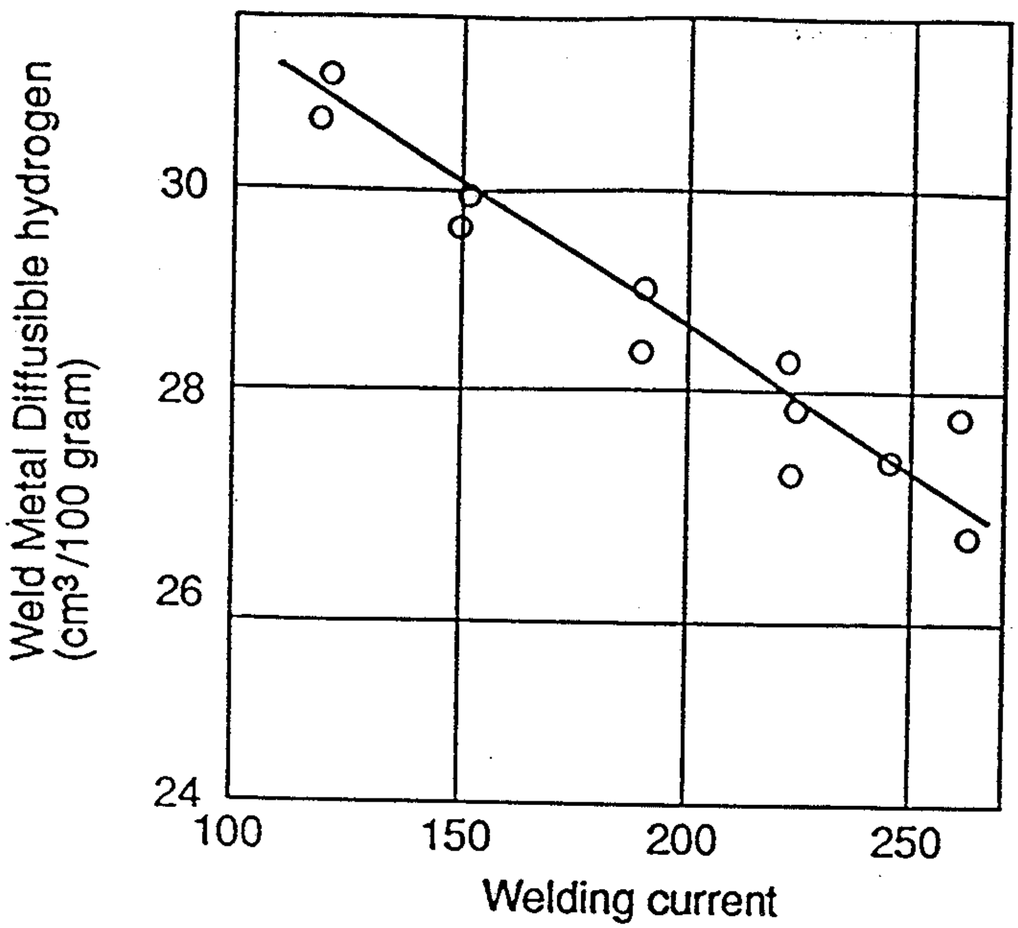

Figure 33. Effect of welding current on the hydrogen content of wet underwater weld deposits (70).

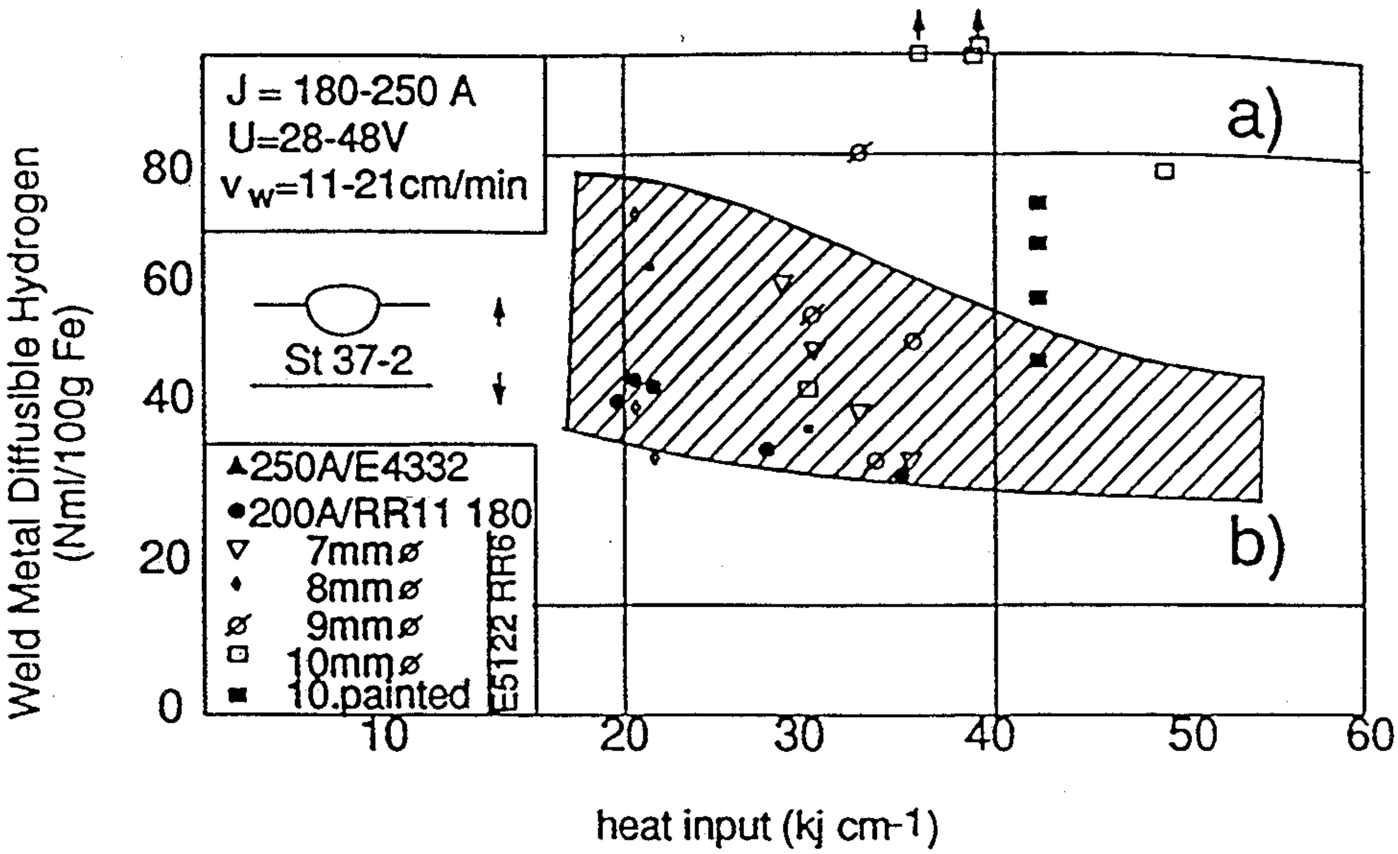

Figure 34. Effect of heat input on diffusible hydrogen and HAZ peak hardness underwater wet SMA welding of 0.13 pct. carbon, 0.40 pct. manganese (40).

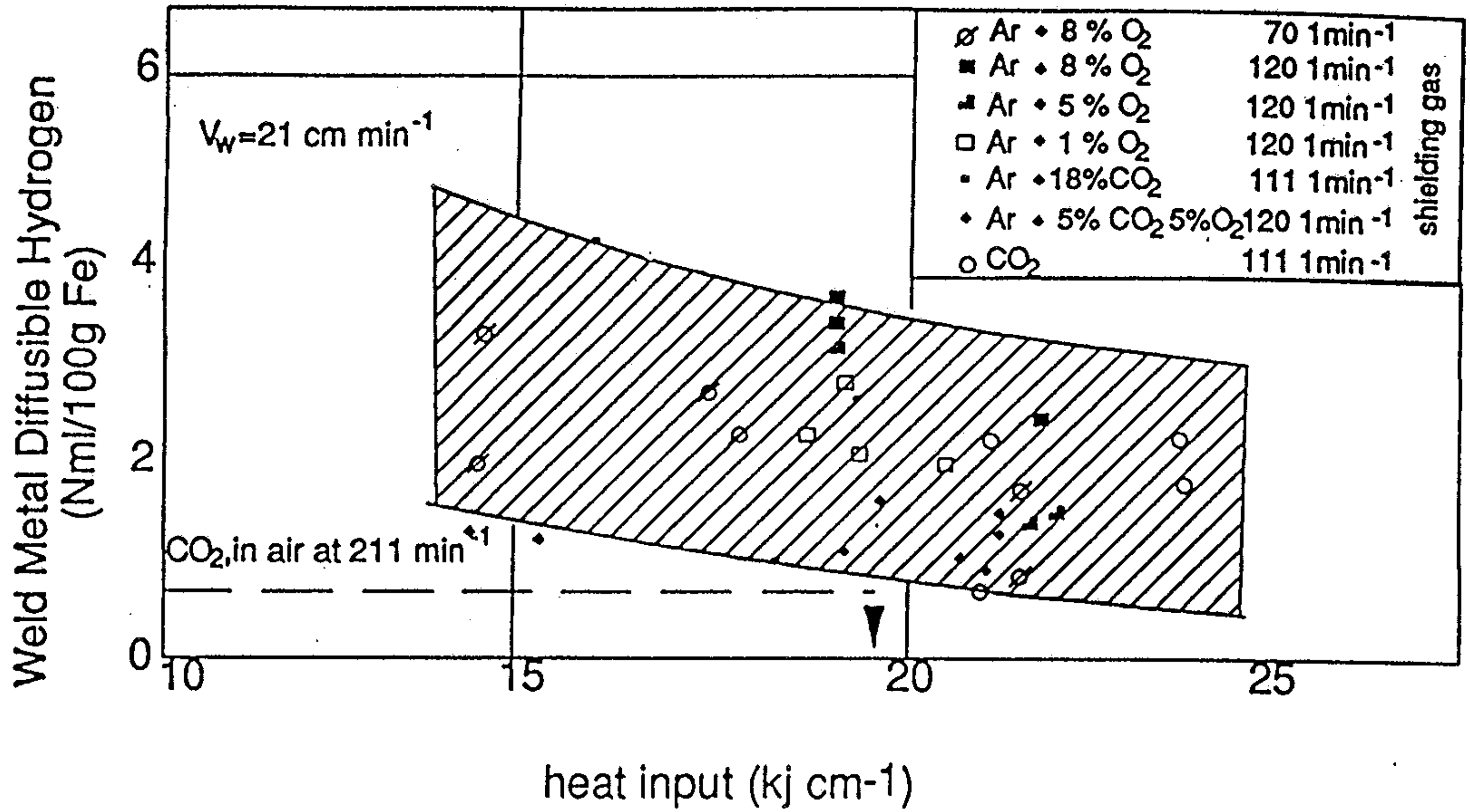

Figure 35. Effect of heat input on diffusible hydrogen content in FCAW underwater water curtain welding at constant water flow 33 liters per minute (41).

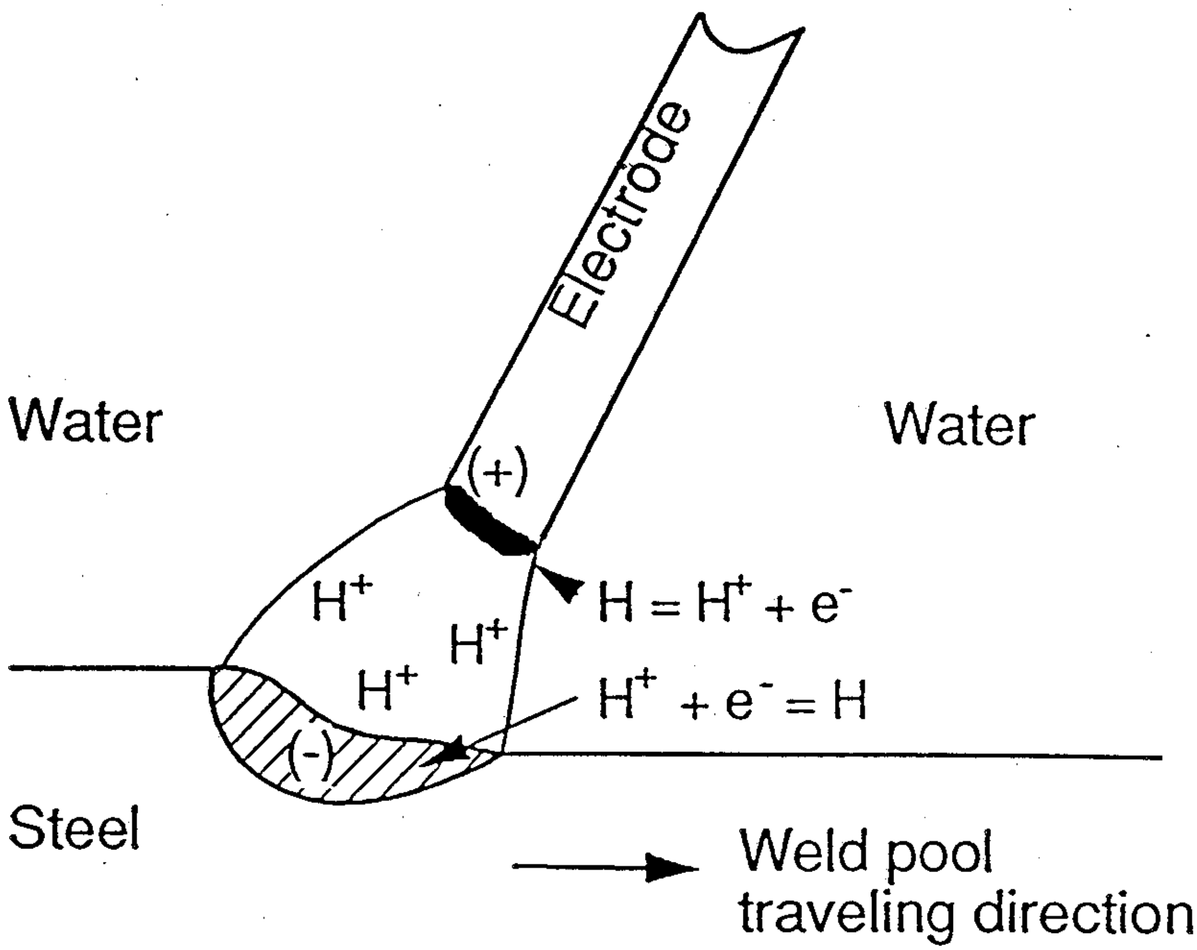

Figure 36. A schematic illustration of the DC welding process as an electrolytic cell. The weld plasma is an electrolyte and the electrode weld pool serves at sites for electrochemical half cell reactions which are strongly influenced by the current density.

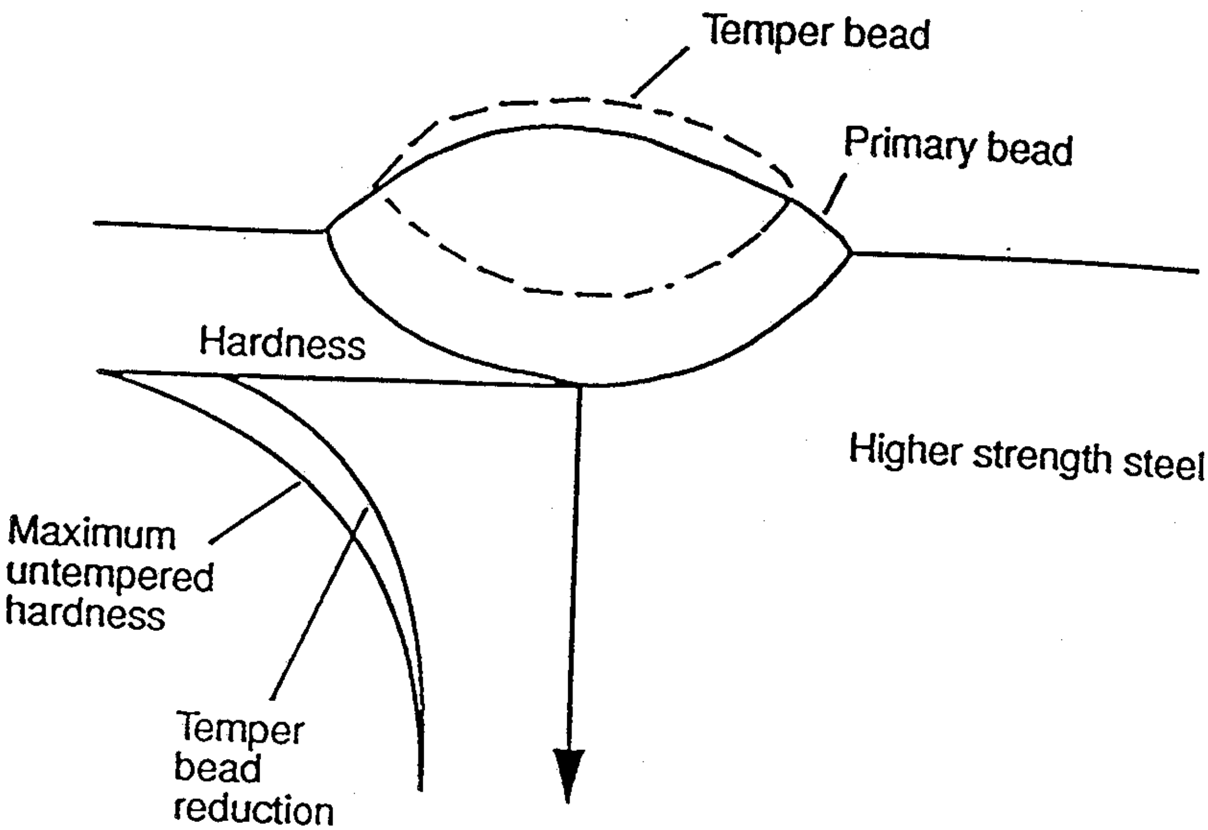

Figure 37. A schematic illustration of the use of temper bead practice to reduce HAZ hardness and the susceptibility to underbead cracking (64).

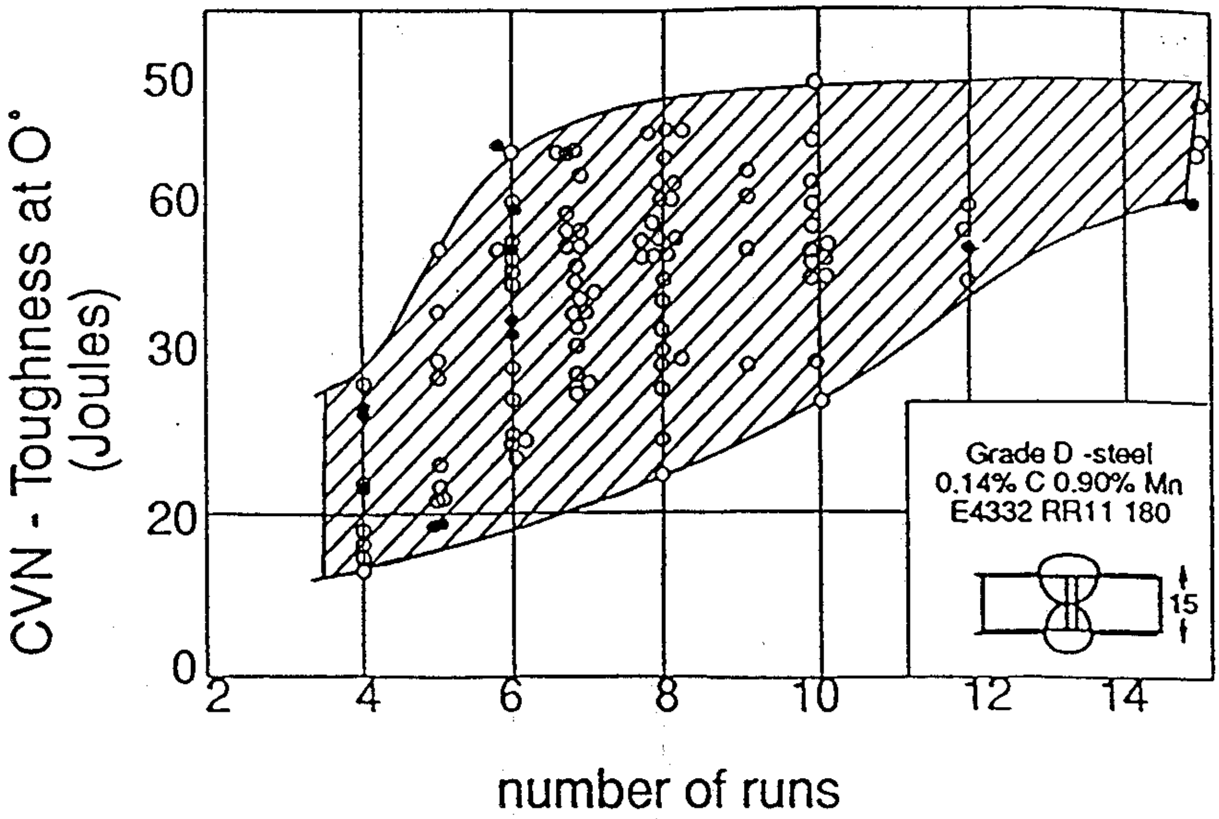

Figure 38. The effect of number of runs of 0°C CVN-toughness of underwater SMA Grade D-steel weld metal (40).

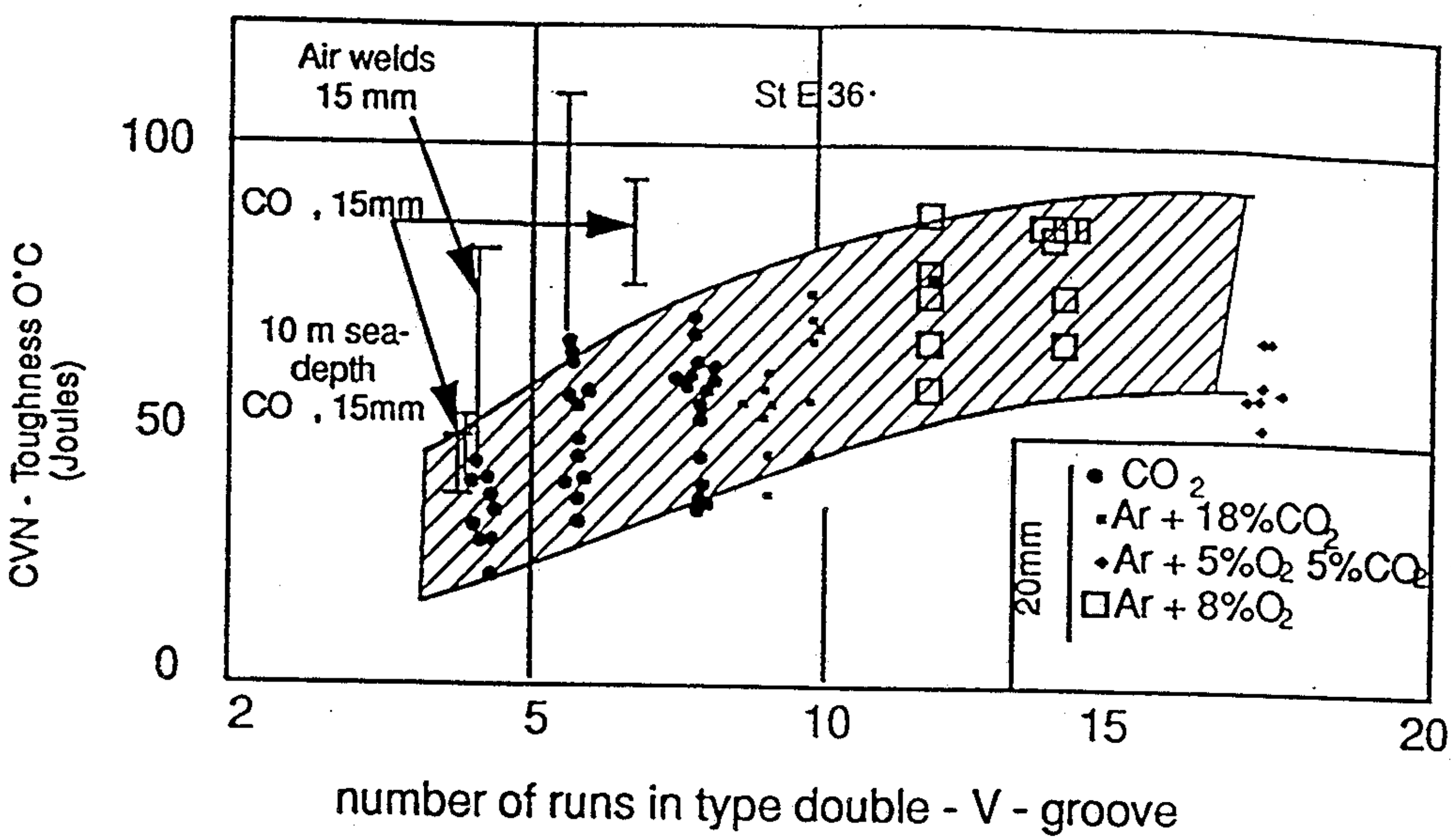

Figure 39. The effect of number of runs on CVN-toughness of FCAW underwater weld metal of 15 and 20 mm St. E36 plates using different shielding gases (41).

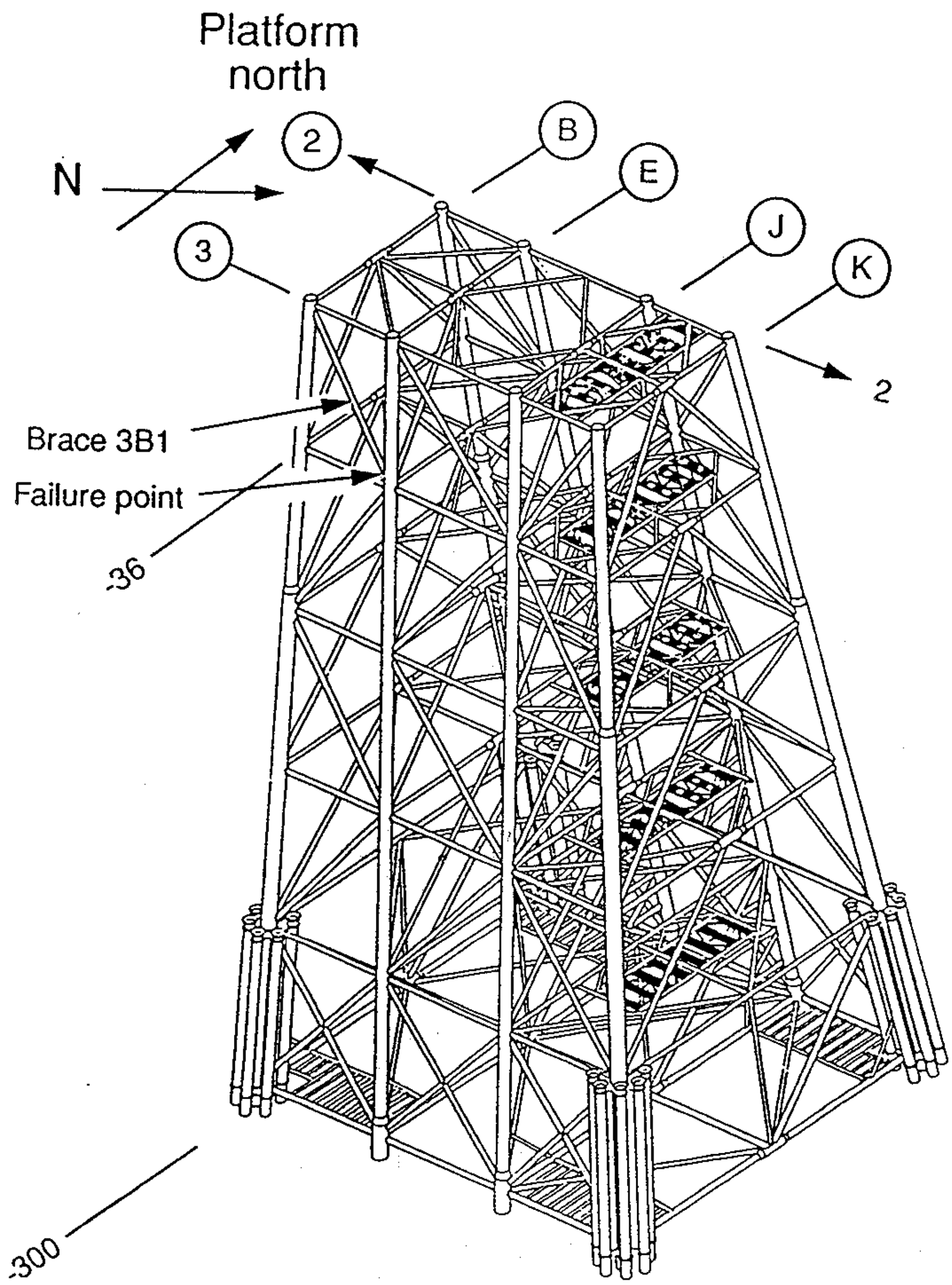

Figure 40 Jacket leg of north sea platform showing the location of the brace that was replaced after collision with the workboat.

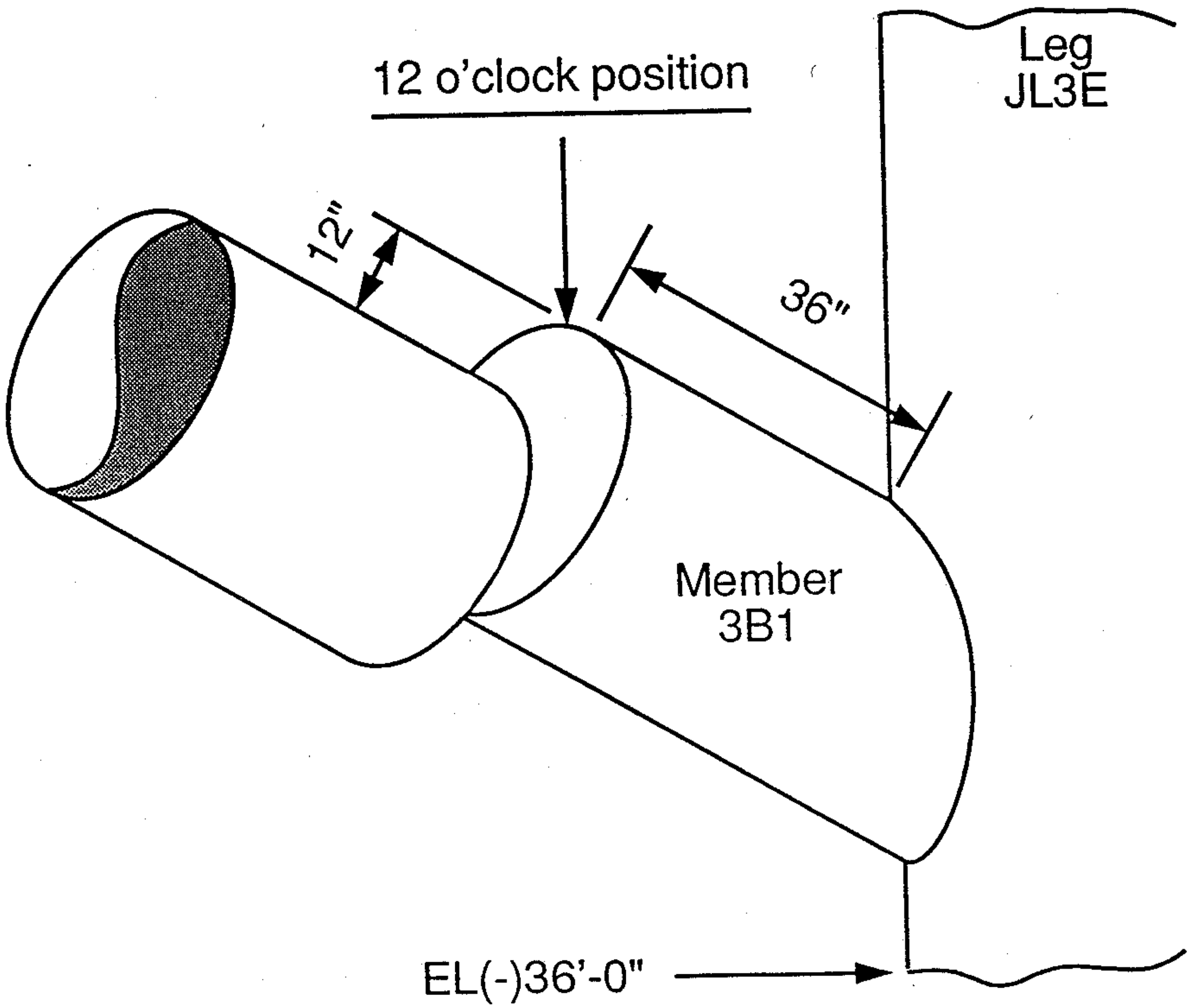

Figure 41 The brace separated fromthe stub at a circumferential weld.

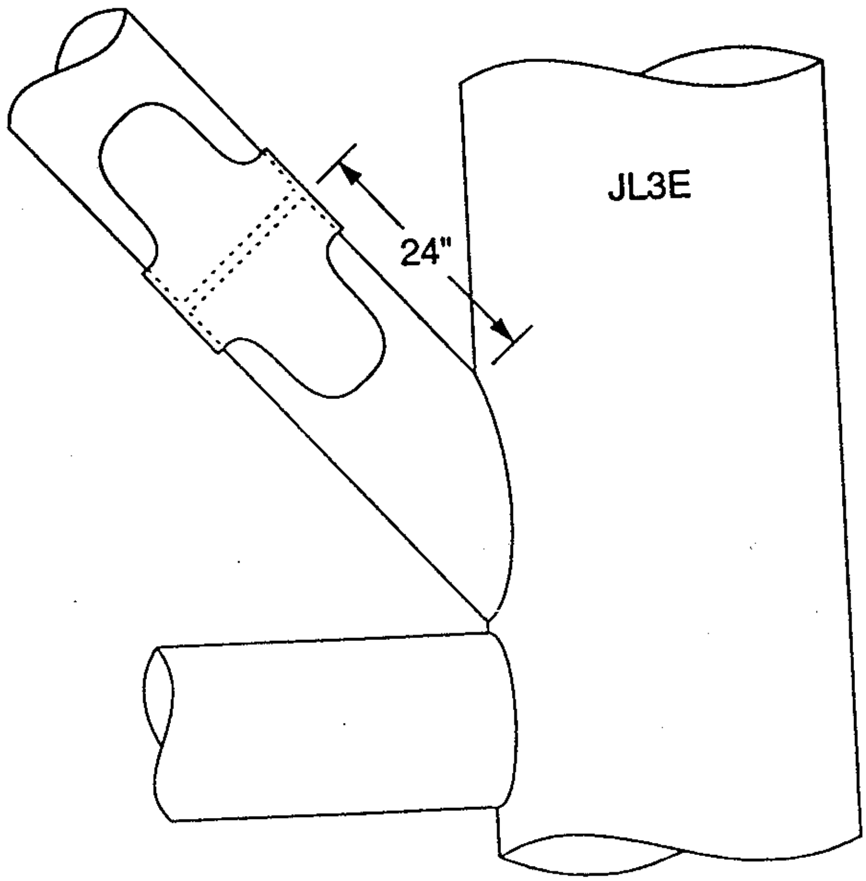

Figure 42 The proposed replacement shows a scalloped sleeve connecting the remaining stub to the new brace member. The scalloped sleeve was wet welded to the stub.

State of the Art and Practice
of
Underwater Hyperbaric Dry Welding

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Introduction

Nine years ago in November 1985 [1] some of this year's participants attended already the last "International Workshop on Quality in Underwater Welding" which was held at that time at the Colorado School of Mines in Golden Colorado. The State of the Art Report in Underwater Welding then had been presented by no less than Professor Harry Cotton, BP. UK. There was only one real welding procedure existing for high quality welds in his understanding: the hyperbaric dry welding procedure. For his understanding with the application of the Wet Welding procedure no one was able to produce any reasonable quality. The expression "Hyperbaric Welding" stood for "dry hyperbaric welding" and no one would have made any consideration in this respect to the wet welding process. Today this must be changed: within the past nine years the weldment quality produced in wet environment has changed remarkably and improved to such an extent that the wet welding procedure has become in certain depths already a viable alternative to hyperbaric dry welding. Now the expression "Hyperbaric Welding" has to be considered from two different aspects: either for the dry or for the wet application. My presentation today will only deal with the **State of the Art and Practice of Hyperbaric Dry Welding.**

General Aspects in Hyperbaric Dry Welding

Hyperbaric dry welding has been applied now for several years on load carrying structural members of platforms and offshore structures as well as in pipeline welding [2]. Today the conventional welding processes such as the Shielded Metal Arc Welding process (SMAW), the Gas-Tungsten Arc Welding process (GTAW), the Gas-Metal Arc Welding process (GMAW) and the Flux-Cored-Arc Welding process (FCAW) have been developed in intensive research activities [3]. The influence of the ambient pressure and the shielding gas on the droplet transfer and the burn off of the alloying elements, the influence of the shielding gas flow rate on the shielding effect and mixture on the process stability and the weldment microstructure and its mechanical properties have been investigated by several well known research institutes all over the world. All these efforts have resulted in improvements of the process and in modifications of the consumables [3-12, 20]. They have developed these processes up to a stage of high performance processes for onsite application down to waterdepths in the range of 500mwd. The achievable high weld standard in reproducable quality and the safe and accurate performance of the process has been demonstrated in qualification dives e.g. in 450 mwd.

During the past years significant efforts have been carried out to develop the hyperbaric dry welding procedures especially for greater water depths and to improve the weldment quality down to 500 mwd and deeper [13,14]. Together with enhanced quality, highest possible production rates are desirable, which the GMAW-procedure in a ratio of 4 : 1 over the next fastest method than the fully mechanized GTAW systems, achieves. [15] As the increasing depths increase the work load for the diving personnel extensively special emphasis is still directed to the development and improvement of mechanized systems to reduce the work load on the diver. Apart from this the introduction of new materials have brought new welding processes into the field for which research and development activities have been started.

Nowadays it is well understood that most of the efforts were concentrated on mechanization and automation of the welding process to reduce the heavy depth related stresses on the diver welder.[13, 16-19]. Therefore Hyperbaric Dry Welding has clearly to be differentiated in manual and automated processes of which the mechanized and automated processes are facing increasing interest. Before going more into the specific details of manual or mechanized welding processes the main aspects that influence the process behaviour and the resulting weldment quality will be explained briefly.

a.) Ambient conditions.

Under hyperbaric conditions the increased ambient pressure and increased thermal conductivity of the gases result into an increased potential drop and an arc constriction over the arc column [11, 12, 14, 20-22] Moreover, this arc constriction in case of e.g. hyperbaric dry metal arc active gas welding and the associated energy density leads to substantial changes in the anode and cathode behaviour[20], the extent of which is determined by the relevant welding voltage and the selected polarity. Negative workpiece polarity results in an increased vaporization of some special alloying elements from the base metal on the focus spot directly below the arc. This phenomenon increases with increasing ambient pressure. The generated cloud of metal vapour apparently flows from surface as a vapour jet or plasma stream [20, 21]. Arc instabilities, reflecting into arc extinctions or into irregular metal transfer modes resulting in increased spattering and intensive fume/ smoke formation are attributed to this phenomenon.

On account of the pressure-dependent energy distribution over the constricted arc, welding parameters for low thermal input (low current and voltage) with a droplet transfer in short circuit transition (in the GMA-Process) produce a narrow and excessive bead height combined with the possibility of an increased risk of incomplete fusion effects that require comprehensive grinding work between the individual passes in order to ensure a satisfactory joint. Therefore it is unavoidable to raise depth related aspects to the electrical parameters to ensure that a sound and smooth bead shape is formed.

The influence of the ambient pressure on the chemical composition of the weld metal deposit is expressed by three basic mechanisms:

* The reduction of the anode and cathode spot based on the pressure-related arc constriction leads to an increase in the energy density and thus to higher temperatures in both spots. As a consequence of this more filler material vaporizes and the burn-off of alloying elements in the arc increases .

* The arc constriction and the increased energy density influences the weld pool geometry and in particular the penetration depth. Changes in the chemical composition of the molten weld pool directly below the arc related to the vaporization of the alloying elements affect the surface tension of the molten metal and thus the flow properties of the liquid weld deposit.

* Gas absorption in the molten weld deposit increases with increase of the ambient pressure. Apart from the general and fundamental increase in oxygen, nitrogen and hydrogen content chemical reactions based on the manganese and silicon proportions of the filler metal control the desoxidation process. This results to a decrease in the proportion of both elements (Mn and Si) in the weldment and thus to an increase of the Mn- and Si-oxides in the slag. Simultaneously an increase of the carbon content of the weld metal deposit can be observed.

Because of the well known mutual influences of the individual mechanisms no clear statement can be given so far concerning their relative effects on the properties of the weld deposit.

The majority of the reported research activities on gas-shielded welding processes (GMAW-process) have been carried out as fully mechanized experiments mainly operating in an inert chamber gas atmosphere (mainly in argon atmosphere). In such cases no problems arise in respect to weldment contamination through the chamber atmosphere. The amount and composition of the shielding gas itself was not an integrated part of the research activities. Only when the experiments have been performed under realistic operational aspects in a breathable atmosphere (even in a nitrogen enriched atmosphere) the amount and composition of the shielding gas and its influence on the arc stability, the droplet transfer and the weld metal properties came into the picture. Various investigations on this problem have presented a good knowledge in this field. e.g. irrespective of the shielding gas involved, the arc stability is more and more disturbed with increasing working depths. With increase of the ambient pressure the arc stability becomes more and more uncontrollable and the arc deflection as well as the rotating possibility of the arc generation point on the electrode tip increases [11]. This results in an increasingly uncontrollable droplet transfer into the weld pool. Until today this phenomenon has not been explained completely and a number of reasons are still made responsible for it. Some of these explanations are related to the production of the pipelines themselves (steel processing, thermal controlled rolling, grain refinement techniques) and the test conditions performed, some are related to the seam preparation or to the permanent magnetism present in the base metal related to the storage conditions or the deposition time on the seabed.

Arc instability especially in the GTAW-process under hyperbaric conditions is a severe problem as this process is conducted under low electrical energy input [5, 12, 21, 22]. Some of the investigators are concentrating on the influence of the operating parameters on the susceptibility of the plasma arc to deflection under the special effect of hot wire application. It was found, that due to the particle interactions in the arc column the welding arc is increasingly susceptible to disturbance by the transverse component of an externally generated magnetic field. The particles are subject to forces due to the local electric field and of the local and applied magnetic fields. The degree of distortion due to an applied field is governed by the mean drift velocity of the charged particles toward the electrodes. The greater the mean velocity the smaller is the lateral component of deflection. As pressure increases the particle density increases and the mean free path of the particles is reduced. This results in a reduction of the mean drift velocity and the field will act on a charged particle for longer resulting in an increased overall deflection.

The experimental results obtained show that for small applied magnetic fields the arc column undergoes a lateral displacement without any significant distortion [12]. This appears to be true for free burning and constricted plasma arcs at low and moderate pressures (< 8bar). Whereas the transition from the undistorted to the distorted arc is discontinuous for pressures <8bar, the behaviour at high pressures is less well defined and the experiments indicate a relatively smooth transition between the two states. At high pressures the arc is adopting a curved path between anode and cathode spot under the influence of a transverse field and the distinction between high and low field regimes diminished. This behaviour is explained in terms of a change in the arc energy balance from an electrode dominated discharge at one atmosphere to column operation at high pressures. When an arc blow occurs during an actual hyperbaric operation it is most likely that the arc will be subject to highly non-uniform fields, intense field gradients will therefore exist. Laboratory simulations indicate that the arc becomes highly unstable and the probability of arc extinction increases significantly.

Another researcher tried to generate a magnetic field around the tungsten electrode for arc stabilization in the TIG process [5]. For this reason a coil with 500 turns of a 0,6mm enamel wire had been placed around the tungsten electrode. The application of a coil current in the range of 3A produced a corresponding magnetic field in the welding area of up to 140 Gs. The electrode extension out of the coil was 5 mm. Bead on plate welds on mild steel under a pressure of 21 bar with a welding current of 100 A and a welding speed of 20 cm/min have been performed with an arc length of 2 mm. The weld bead appearance without an external magnetic field showed a meandering bead due to the destabilisation of the arc under the influence of the ambient pressure. The application of a static magnetic field of about 120 Gs, straight and sound welds have been produced. However, the shape of the weld bead became often unsymmetrical with respect to the weld line and irregular ripples occur at the toe area in a higher magnetic flux density. Applying an alternating field, straight and sound welds without the above mentioned irregularities have been achieved. Any considerable differences in the bead appearance caused by the frequency of the magnetic field were not observed.

<u>b) Shielding gas</u>

Investigations in the shielding gas flow rate for the GMAW-process, carried out by several researchers (Fig. 1) [7], distinguished an optimum gas mass flow of 10l/min for the GMA-process to preserve the weld pool from contamination with gas components out of the chamber atmosphere (e.g. from nitrogen or hydrogen). Turbulence in the shielding gas stream lead to reduced charpy values (Fig.2). This figure, prepared from results out of specimens welded underdry hyperbaric conditions in 360 mwd, clearly demonstrates, that an undisturbed shielding gas flow (curve a) provides a weld metal with higher charpy values at the operational temperatures and therefore better ductility than a disturbed one (curve b) [8]. The experimental conditions have been selected as follows: chamber gas = Trimix ($He/O_2/5\%\ N_2$) ; shielding gas = He/CO_2; consumable = specially designed flux core wire with C-Mn-1%Ni; base metal = pipeline steel API 5 LX 65 (StE 445.7TM DIN 17 172).

The wire/flux concept [20] in flux cored consumables apparently offered a number of advantages over both, the bare wire GMAW and the SMAW process. Metal/flux combinations are more thermally efficient and fluxing ingredients can be added which improve arc ionization and promote stable metal transfer. An adequate flux formulation and shielding gas selection could

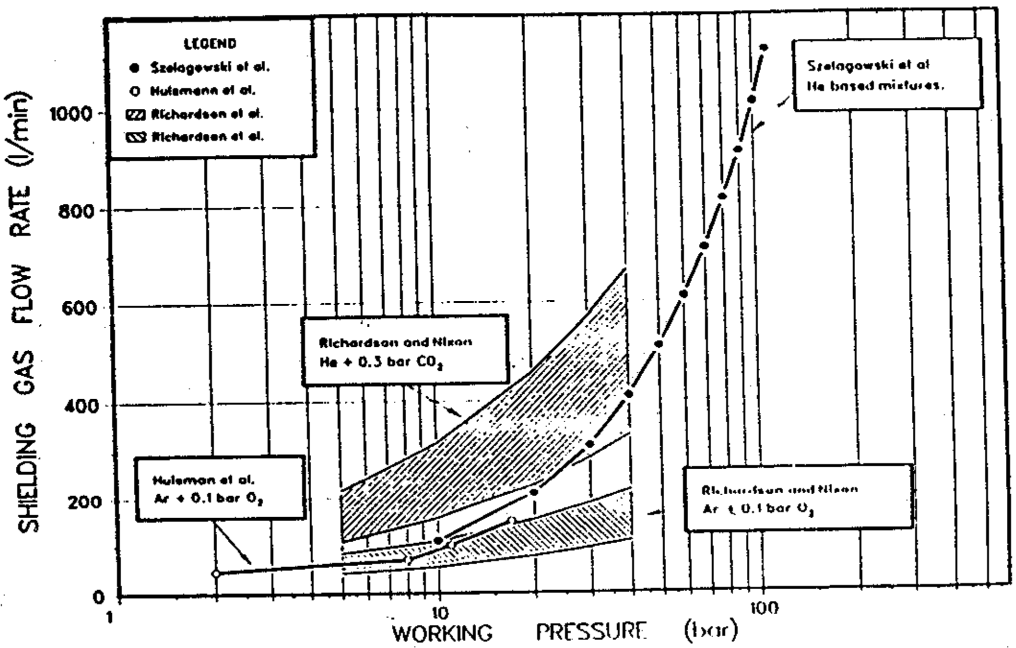


Fig. 1: Shielding gas flow rates as a function of ambient pressure

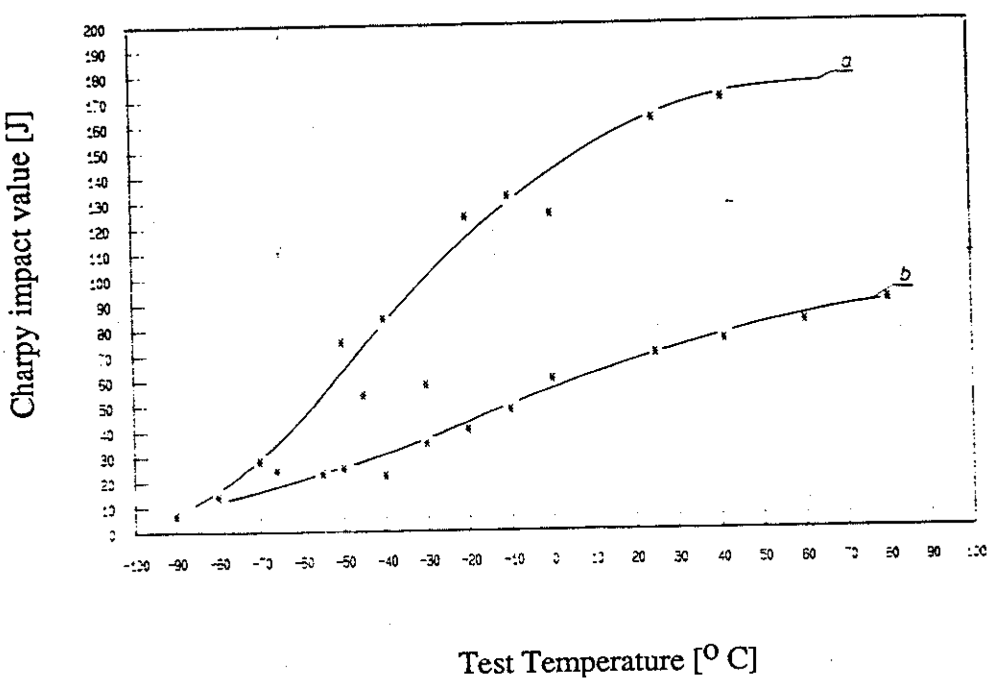


Fig. 2: Charpy impact values achieved from weldments produced in 360 mwd (Shielding gas stream: a) undisturbed, b) disturbed.

offer the possibility of:

a) a stable metal transfer due to a balance of fluxing ingredients and gas shield.

b) control of weld metal chemical composition by manipulation of the shielding gas composition and balanced addition of deoxidants

c) higher heat input levels applied to the workpiece offsetting heat losses due to the effect of pressure

d) higher metal deposition rates in all welding positions

e) high duty cycle due to the continuous nature of the process

f) higher tolerances to parametric variations.

The influence of oxygen on the weld metal properties generated from the active gas mixture out of He and CO_2 or He and O_2 has been carefully investigated in different simulated water depths. Fig.3 presents published relationships between oxygen and CO_2 partial pressures

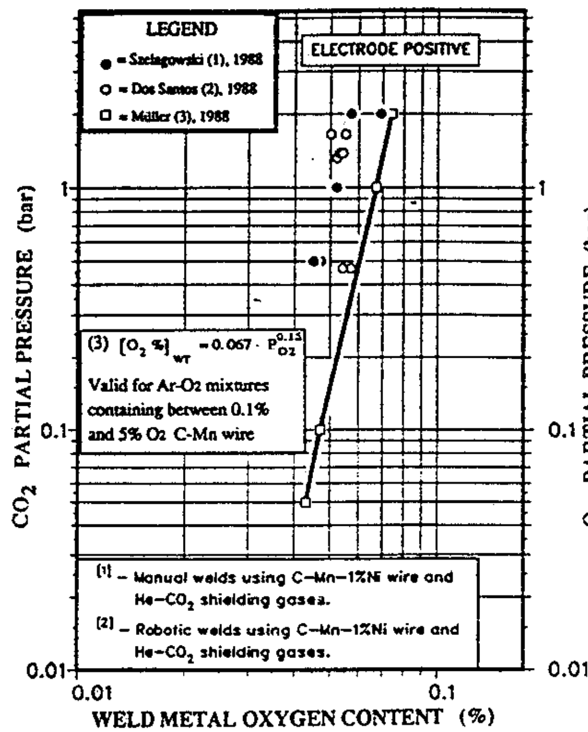


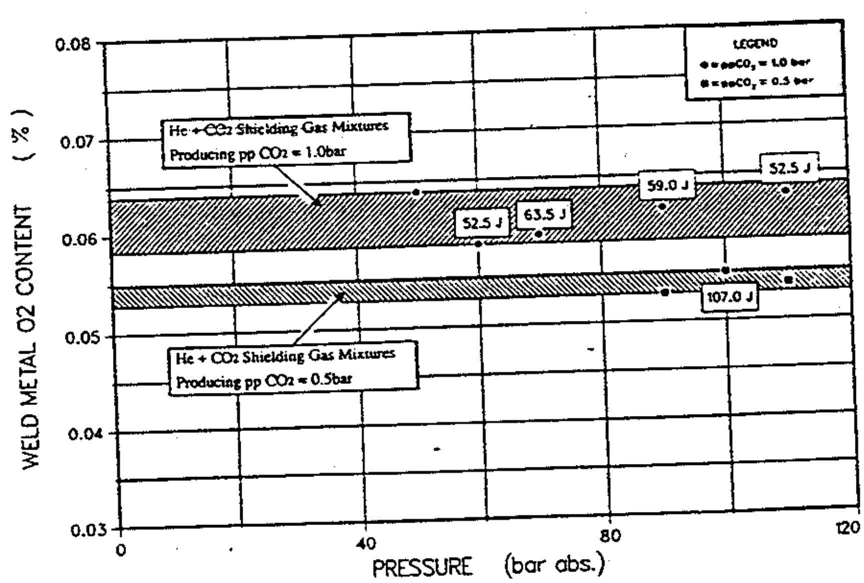
Fig. 3: Relationship between shielding gas activity and weld metal oxygen contents.

(in the shield) and the resulting weld metal oxygen contents, for C-Mn and C-Mn-1%Ni flux cored wires, welded with positive polarity. As indicated in this figure, with the exception of the selected polarity which is common to all specimens, these results cover a wide range of experimental conditions. The most significant differences to be taken into account are:

* Shielding gas compositions presenting active components partial pressures between 0,020bar and 1,5bar for oxygen and 0,015bar and 2,0bar for CO2. Both Ar and He have been used as carrier gases.

* The specimens produced during the manned experiments have been welded in different positions by a group of welder divers with various degrees of skill and experience. This resulted in a wide range of welding parameters and weaving techniques. On the other hand, the specimens produced during mechanized welding experiments were welded under comparable conditions, e.g. welding parameters and technique (stringer bead) as well as equipment (power source, cables, gas nozzle, etc). It is important to note that the different operational modes (mechanized and manual) represent different degrees of arc stability. The mechanized welds have been produced using higher energy procedures (higher voltage and current) than that applied by the diver-welders. These higher energy procedures resulted in reduced short circuit frequencies and higher temperatures in the arc column and weld pool, all of which significantly affect oxygen absorption.

The use of constant CO_2 partial pressure in the shielding gas resulted in nearly constant weld metal oxygen contents throughout the pressure range studied (for $ppCO_2$ = 1bar, 0,058% to 0,064% O_2, and for $ppCO_2$ = 0,5bar; 0,053% to = 0,055% O_2) for deep water application (between 600 mwd and 1.000 mwd). As expected higher CO_2 partial pressures resulted in higher weld metal oxygen contents. The charpy test results at -20°C presented higher impact energies with lower weld metal oxygen contents. (Fig.4) [22]. Nevertheless, the impact energies obtained



Figures inside the squares indicate the Charpy impact energy at -20° C.

Fig. 4: Weld metal oxygen contents obtained at different working pressures

within a pressure range of 60 to 100 bar varied between 52 J to 107 J depending on the shielding gas mixture which comply with the standards conventionally employed for offshore constructions.

The selection of low active gas partial pressure in the shield (micro additions) result in weld metal oxygen levels below 0.045%. The use of negative polarity has been also considered as a favorable element to achieve these levels. It was found that by using negative polarity and low 0.5 bar CO_2 partial pressure in the shield, have produced weld metal oxygen levels below 0.045%. Similar results have been reported using Ar-0.3% O_2 in the pressure range from 15 to 100 bar (O_2 partial pressures between 0.05 bar and 0.3 bar). In this case however, the use of a constant O_2-volume in the shield (for all welding pressures) resulted , as expected in a progressive increase in weld metal O_2-content (from 0.025% O_2 at 1.5 bar to 0.053% O_2 at 100 bar).

Oxygen mainly forms silicon-oxide inclusions. Their distribution density increases with the oxygen content and influences the microstructure formation during the cooling phase. A raised amount of silicon-oxides limits the growth of the austenitic grain formation [24]. This results in smaller austenitic grains. During the progress of the cooling phase the austenite-ferrite transformation increases the amount of boundary ferrite and the side-plate formation, the amount of acicular ferrite is reduced. As a reason of this cracking can occur mainly in the boundary ferrite zones. Therefore it is obvious that the shielding gas composition has to be carefully selected.

The presence of a slag system, to support and mold the molten metal would improve the bead contour being also of great assistance to positional welding. The achieved results with such wires showed excellent weldability, fusion and mechanical properties in all positions. A seamless wire for hyperbaric dry application, which complies to the AWS classification A5.29/E80T5-G is available and successfully applied. Two main variants of this wire are produced: a standard C-Mn type and a C-Mn-1%Ni version with higher strength suitable for fine-grained structural steels. Some limited investigations have been carried out with "modified" versions of these wires. These modifications came about as part of systematic investigations on the consumables properties and the attempt to improve weld metal chemical balance and therefore microstructural and mechanical behavior. The investigations with these wires lead to the following conclusions:

1. The concept of optimum shielding gas flow conditions for hyperbaric FCAW should be based on two criteria: arc stability and effective shielding action. In practical terms, the latter has to be primarily fulfilled in order to avoid excessive weld metal contamination by hydrogen or nitrogen.

2.) It has been conclusively shown that for a given shielding gas composition increasing ambient pressure leads to higher weld metal oxygen contents. A relationship between O_2 partial pressure and the expected weld metal content has been proposed for Ar-O_2 mixtures containing between 0,1% and 5%O_2. Low active gas partial pressure in the shield (in order of 0,1bar to 0,3bar) leads to oxygen levels required for a satisfactory weld metal toughness.

3.) Equilibrium expressions describing the dependence of C and oxygen levels on the partial pressure of CO_2 and O_2 in the shielding gas have been shown also to apply to high pressure systems requiring a proper selection of the values for pressure, reaction temperature and the dissociation degree of CO_2. In case of hyperbaric FCAW, for a given working pressure, the increased availability of CO and CO_2 leads to higher carbon equilibrium levels in the weld pool. With increasing pressure, upon reaching the critical temperature, carbon oxidation in the liquid metal is no longer thermodynamically fa voured, giving place to desoxydation through Si and Mn.

c) Material properties.

Unalloyed and low alloyed structural steels with raised carbon equivalent are the common steel materials for offshore application. These steels tend to harden in the Heat Affected Zone (HAZ) if the "critical" cooling rate is exceeded. The ambient conditions in hyperbaric dry atmosphere with Helium as the main component of the chamber gas do not permit moderate cooling rates because of the high heat conductivity effect of the helium. To avoid high hardness pre-weld- and/or post-weld heat treatments are carried out in field operation. In manual welding the diver welder is very much affected by pre-weld heat treatment as the temperatures have to be raised generally above 120°C. Therefore in manual hyperbaric dry welding the pre-weld heat treatment method is only applied on very critical materials under severe precautions for the diver welder.

Materials strength and hardness in combination with decreasing ductility can increase in the HAZ to such an extent that in certain circumstances cracking will occur already under residual stress loads. The application of especially designed and formulated consumables (e.g. special flux cored wires as mentioned above) in combination with special welding procedures (and if circumstances request the additional procedure, with the above mentioned pre- and post-weld heat treatment procedures) are able to solve the problems of high hardness and cracking. Even the problem of hydrogen contamination of the weld metal and HAZ in combination with hydrogen cracking is generally solved by the above mentioned measures. A correct shielding gas quantity will protect the weld pool properly and guarantee excellent weldment properties.

The development of new steels for pipeline or structural application require certain new consumables which produce a weldment matching the parent material. For quality improvement further efforts have been made to adjust the burn out of chemical elements during the welding process due to the oxygen generation from the humid habitat atmosphere and to increase the dehydrating effects. In these cases some moderate quantities of special elements (e.g. Al, Ti, B) have been added to the flux to equalize the burn off of some elements and to achieve the oxidizing and dehydrating effects. Especially for joining ferritic steels the hyperbaric dry SMA-welding process is well developed and established and is still applied all over the world.

During the recent years significant efforts have been carried out to produce welding consumables for gas shielded arc processes with an alloy composition that meet the burn-off rates elevated pressures and that guarantee a weldment composition using extremely high cooling rates fulfilling the internationally applied standards and qualification requirements. As already mentioned above, the problem of weld pool contamination through the ambient atmosphere is for these processes not a critical factor so that mainly the burn-off rates had to be considered.

Today it is possible to achieve extremely high weldment qualities and joint properties in manual welding down to 500 mwd and in mechanized welding down to 1100 mwd.[14] A properly applied welding process in combination with a correctly selected consumable matching the base metal in combination with the correct shielding gas composition and flow rate will guarantee such excellent results: hardness values below 280 HV 10, mechanical properties (including the charpy values, the bending radii, the tensile and yield strength and CTOD values) in the range of the base metal properties (similar values or exceeding them). In comparison of the ANSI/AWS D3.6-93 qualification criteria Type A weldment quality can be achieved.

Work depth limitations are imposed by the diving mode and the available breathing gas mixtures. Manual and partially mechanized welding on offshore pipelines and structures have been carried out in the depths range down to 220-250 mwd in a dry hyperbaric habitat atmosphere.

Manual Hyperbaric Dry Welding.

The manual hyperbaric dry welding process was developed as a Shielded Metal Arc Welding (SMAW) process applying stick electrodes as consumables. As the welding process is performed in a habitat in an artificial gas atmosphere these electrodes are generally ordinary electrodes without any special water or moisture resistant coating as it is known for electrodes for wet application. Generally, as the atmosphere in such a habitat is quite humid, the electrodes are kept in a heating box or sealed in a pack or are vacuum packed to prevent its flux coating from moisture absorption. Hoffmeister mentioned already during the workshop in 1985 [1] the problem of hydrogen entrapment and in conjunction with this hydrogen induced cold cracking (HICC) generated through the normally unavoidable humid atmosphere in a habitat on the sea bottom [3]. Therefore electrode drying before welding has become an essential part in hyperbaric dry SMA-Welding. Until today this SMAW-Process is a well developed and often applied welding procedure in hyperbaric dry environment. The process is generally applied for root-pass-, hot-pass- and filler welding which demonstrates the wide scope of applicability of the process.

The application of the GTAW-process for root- and hot-pass welding has been accepted by offshore industry due to better handling of the process by the diver welder, better weldment quality (no slag, no slag entrapments), lower hydrogen contamination of the weld metal through accurate shielding gas control. Because of the low performance efficiency the manual GTAW-process is not often used for the filler and cap layers. The process is characterized through a low heat input and therefore through a small and limited weld pool. The amount of molten material is limited and permits an excellent weld pool control especially in out of position welding such as overhead welding. This process advantage benefits in pipeline construction the root pass welding but prevents the manual process from being applied efficiently for filler and cap layers. The production time becomes far from adequate. The thickness of the root pass is so small, that thicker filler layers cannot be applied immediately after finishing the root run: a further layer < the hot pass > is essential before the joint can be built up by the application of other processes. Nevertheless, the GTA-Process has become for the above mentioned application the most appropriate process and is mainly applied for pipeline construction work subsea in manual operation. It has subseeded the SMA-Process for root- and hot pass welding in general. A combination between the GTA- and SMA-Welding process is well known and a very common version for manual hyperbaric dry welding.

Higher performance rates can be achieved by the application of the manual GMAW- or FCAW-Process. For the GMA-welding process a bare wire from low alloyed material is applied as consumable. The alloy combination of this wire is such that the generated weld metal matches the base metal and produces adequate qualities and mechanical properties. The resulting slag, which is merely generated from Silicon-Oxyde, is easily overwelded by subsequent layers and does not produce any slag inclusions and welding failures. This wire can preferably be used in mechanized welding processes because no slag removal process has to be provided.

In the Flux-cored-arc welding process usually the flux contains the necessary alloys in a quantity that takes into account the burn-off rate of a certain amount of alloys and that guarantees a weldment quality that is at least matching the qualities of the base metal [20]. The flux is additionally responsible for the slag production on top of the bead to reduce the cooling rate.

Generally this slag has to be removed before an additional layer can be applied. In certain cases this operation can be difficult and may therefore lead to welding failures in form of slag entrapments. A high work accuracy and attention of the diver welder will only guarantee a good weldment quality.

The above mentioned investigations on the gas flow rate and the combination of the shielding gas benefit these processes. For both of them generally active shielding gases are applied to achieve a good droplet transfer, weld bead formation and weld metal qualities.

Mechanized Hyperbaric Dry Welding.

Since several years there has been remarkable attempts to develop mechanized welding systems that can be operated remotely controlled on the sea bottom and producing reproducable high quality welds[13, 15-17, 19]. The reason for these developments are the attempt to reduce the workload from the diver welder and the exploration activities of oil fields in greater depths. The deeper the diver welder has to work the higher will be the workload on him and the less will be the achieved quality in manual welding. The developments were possible as other welding processes than the SMA-Process have been successfully improved. In recent years experience has been gained in the use of remotely installed and operated equipment for hyperbaric pipeline welding or tie-in operations.

The industrially experienced mechanized welding systems installed in a habitat on the seabed are all surface operated GTAW-systems [17, 19] which require diver´s assistance during the initial set-up and during the performance of routine tasks during the welding operation such as measuring pipe fit-up, changing electrodes, servicing the wire feed and supervising the weld head umbilicals. Today´s attitude is to operate such mechanized systems as much as possible to reduce the stressing hard work of the diver. 220 mwd is the maximum depths in which such mechanized systems have been successfully applied. Efforts are made to go deeper in oil field development and to apply these systems in greater depths as soon as the deep water pipe-laying and tie-in installation work becomes evident.

Mechanized systems are advantageous to manual operations as the process performance guarantees much better uniformity in the weldment quality and with this a much higher reproducability. A manual override of the system guarantees the process related necessary modifications in relation to groove changes, unforeseen distortions, arc deflection etc. Achievable weldment quality with the GTAW-process and (in latest orbital design with the GMAW-process) result in mechanical properties exceeding the base material qualities and meet in this respect the qualification criteria of ANSI/AWS D 3.6-93. The consumables and shielding gas conditions have been evaluated for the mechanized process following the developments as discussed above.

Weldments prepared in 1000 mwd by robot-GMA-welding show similar excellent qualities as those prepared only in 360 mwd or 450 mwd [7, 13, 14]. The necessary shielding gas composition and its flow rate can be selected from the above shown diagrams.

Achievable properties in mechanized welding with different processes for a complete pipe joint in 265 m are listed in table 1 as an example. Similar results have been achieved down to 1.000 mwd in dry hyperbaric mechanized application [16]

	ROOT & HOT PASS GTAW ORBITAL 265 msw	FILLE & CAP FCAW: ORBITAL 265 msw	FILLER & CAP FCAW: MANUAL 265 msw	INTERN. SPECIFICATION BS 4515
VICKERS HARDNESS (10 kg LOAD)				
WELD				
ROOT	196	—	—	< 275
FILLER	—	192	206-247	< 275
CAP	—	200	—	< 275
HAZ				
ROOT	230	—	—	< 350
FILLER	—	226	232-262	< 350
CAP	—	224	—	< 350
CHARPY V-NOTCH IMPACT TEST (-10 °C)				
WELD SINGEL TESTS	—	50 J	—	> 27 J
	—	46 J	—	> 27 J
	—	55 J	—	> 27 J
MEAN	—	51 J	—	> 34 J

Table 1: Weldment properties achieved in 265 mwd

Table 2 shows the chemical composition of steel pipe and weld metal achieved in the welding process performed with diver assistance in 265 mwd under simulated conditions [16].

New developments

Oil and Gas containing large amounts of H_2S, CO_2 or other corrosive chemicals are on the increase due to greater exploitation of sour resources and progress of enhanced oil recovery by seawater or CO gas injection. To transport such oil and gas by low-alloy steel pipe dehydration or desulphurization treatment or inhibitor injection is essential in view of corrosion resistance. Dehydration and desulphurization facilities require huge investment costs, the economy and reliability of inhibitor injection declines in offshore and deep wells. Therefore extended life time and increasing exploitation of aggressive oil and gas deposits require the adoption of materials with out-

	PIPELINE API 5LX X 65	FILLER METAL (SOLID) AWS E70 S-6	FILLER METAL (FLUXCO-RED) AWS E80T5-G	WELD METAL BEAD FILLER LAYER
C	0,09	1,0	0.023	0,07
Si	0,44	0,8	0,31	0,24
Mn	1,57	1,4	1.320	1,13
P	0,015		0,004	0,08
S	0,001		0.005	0,006
Ca				0,035
Cr	0,13			0,07
Ni	0,05		1.11	0,613
Cu	0,04	< 0,3		0,06
Al	0,039			0,02
V	0,07			0,02
N[ppm]	138	49	73-98	120

Table 2: Chemical analysis of weld metal achieved in 265 mwd.

standing corrosion resistance combined with high mechanical strength and good processing possibility. This implemented the introduction of new materials such as Cladded Steels, Duplex Stainless Steels or Titanium and Titanium Alloys as pipe material for offshore application [23-30]. One of the main problems e.g arising from hyperbaric welding in a habitat is the oxygen contents in the chamber gases and the avoidance of its access to the weld metal especially in root pass welding. Direct through purging of shielding gas from inside the pipe will result in disturbance of the weld pool due to the gas flow. Large efforts have been made to develop special welding procedures for onsite production. First attempts are to provide a well sealed plastic tent around the welding area enclosing the process completely. Nevertheless, only a few investigation have been reported for hyperbaric welding of such exotic materials.

Cladded Steels have been introduced to benefit the high strength from an unalloyed or low alloyed ferritic base metal and the corrosion resistance from a cladded corrosion resistant alloy (CRA). It is obvious to say that the manufacturing process of such a pipe material is difficult and requires certain attentions. The required corrosion resistance of the CRA-layers is achieved in the as-rolled condition by optimizing the thermomechanical control process (TMCP) conditions for production of the clad plate [24]. In order to obtain good corrosion resistance properties of the cladded layer it is necessary to ensure complete recrystallization and suppress the precipitation of chromium carbides in the layer after rolling. However, conventional steel high temperature rolling causes a considerable deterioration in the low-temperature toughness. Therefore , a low C-high NB-Ti-microalloyed steel, has been developed and selected as base metal. This steel exhibits a fine-grained microstructure even under high temperature rolling. Joining such cladded pipe materials requires new welding procedures and probably even new welding processes especially for the hyperbaric dry application.

Welding as applied under atmospheric conditions for joining the seems of the rolled pipe has to be similarly carried out under hyperbaric conditions. This can be performed by applying a low alloy High-Nickel-Alloy consumable for the total joint. Another possibility is to weld the first pass between the cladded layer and the microalloy steel with a low alloy consumable, the inner part (cladded part) of the pipe by a high-alloyed wire and the outer part (microalloyed steel pipe) with the submerged arc process. How far these mentioned procedures can already be applied under hyperbaric conditions has to be proved. Field tests under atmospheric conditions employed the GTAW-process using consumables of which the alloy composition was mating to the cladded material. The butt joints prepared from outside the pipe showed mechanical properties similar to the base metal and low hardness values (about 248 HV10). Corrosion tests on such pipes showed then to be acceptable to good corrosion resistance values even in the welded zone. The welding performance under hyperbaric conditions have to be tested.

Another solution to the corrosion problem of such exploitation products are pipes produced from **Duplex Stainless steels.** [23, 25-28]. Duplex stainless steels are alloys characterized as consisting of two phases: the austenitic and the ferritic phase. As such they combine the benefits of both phases i.e. the good ~~ductility and~~ general corrosion resistance of austenite, but with improved stress corrosion cracking resistance and strength associated with ferrite. In general, ferritic-austenitic (Duplex) stainless steel consists of 40-60% of ferrite and a typical composition of 22% Cr-5,5% Ni-3% Mo-014% N [25].

To ensure optimum properties carefully controlled manufacturing techniques are employed to produce this combination in roughly equal proportions. To benefit from the superior properties of duplex stainless steels, it is vital that these alloys can be welded effectively and that the properties of the welded joints match those of the parent metals. The situation however, is not that simple, as the material state is of prime importance, cold worked material can show a marked difference in corrosion resistance properties to a solution annealed product. The austenite/ferrite phase balance and the alloy partitioning between the phases in the base material also has a significant effect on the post weld heat treatment. Trials in welding duplex stainless steels of the ASTM A 790 S 31803 or DIN 14462 with consumables of similar composition gave a rise to a low austenite phase fraction (< 25%) and associated poor weldment toughness and corrosion resistance. Under hyperbaric conditions these steels are normally welded using the GTA welding process which is characterized by slow welding speeds and low deposition rates. However, in the North Sea alone, until 1990, approximately 250 km of duplex pipelines have already been laid and duplex pipe-laying is still a growing business. As a result of this increasing application of duplex steels in subsea pipelines it is almost inevitable that some underwater welding of these materials will be required. Therefore improvements in welding efficiency is needed.

In order to improve this efficiency and reduce operational (i.e. bottom) times the use of high deposition welding processes like GMAW would be of advantage.[23, 27, 28] However, in the hyperbaric GMAW process a series of pressure dependent (or affected) factors such as metal transfer, active gas absorption and bead geometry still require some degree of clarification. In this study different shielding gas mixtures down to 300mwd have been applied in a breathable chamber gas atmosphere consisting of a Trimix mixture (95,63% He, 0,85% O_2, 2,93% N_2 and 0,59% CO_2). The shielding gas composition and the active gas partial pressure are found in table 3.

SHIELDING GAS COMPOSITION	ACTIVE GAS PARTIAL PRESSURE (bar)			
	1 bar	11 bar	21 bar	31 bar
50% He + 50% Ar	0	0	0	0
0.1% O2 + 30% He + 69.9% Ar	0.001	0.011	0.021	0.031
0.1% O2 +0.2% N2 + 30%He+69.7% Ar	0.001/0.002	0.011/0.022	0.021/0.042	0.031/0.062
0.1% CO2 + 30% He + 69.9% Ar	0.001	0.011	0.021	0.031

Table 3: Shielding gas composition and active gas partial pressure

The operational parameters are listed in table 4.

PARAMETER	SELECTED VALUE
Working pressure (depth)	1bar, 11bar, 21bar and 31bar
Shielding gas composition	see Table 2
Shielding gas flow rate	mass equivalent to 10l/min at the working pressure
Chamber gas composition	Trimix (see item 2.1)
Chamber temperature	20 - 30 °C
Welding speed	4.8 (mm/s)
Wire-feed rate	7.0 (m/min)
Slope characteristic	3.0 (V/100 A)
Current (minimum background)	30A at 1 bar 80A for the other working presures
Open Circuit Voltage	65V
Voltage (Power Source Setting)	20V ± 1V
Current Rise Rates (Power Source Setting)	40%-50%-60%-70% (according to the working pressure)
Current Fall Rates (Power Source Setting)	50%-60%-70%-80%-90%-100% (according to the working pressure)
Welding position	downhand
Torch to plate distancé	15 (mm)

Table 4: Welding and environmental parameters used

The results of these tests show that a"mixed" transfer mode (short circuit with minor periods of open arc) is the most suitable one due to the advantage it gives to positional welding [23]. To achieve an acceptable level of short circuit metal transfers it was found that a voltage setting at a power source controller of 20V+/- 1V was required for the pressure range covered in the experiments. No significant or systematic influence of the addition of either O_2, CO_2 or N_2 to the shielding gas on the stability of metal transfer has been observed. It is well known that under hyperbaric conditions, the increased thermal conductivity of gases causes constriction of the welding arc and an elevation of the potential drop across the arc column which is proportionally related to the square root of the ambient pressure. Additionally, arc constriction results in an increased energy density which promotes substantial changes in cathode and anode behaviour. Increased base plate material vaporization and intensive fume formation as a result from change has been reported above. In case of ferritic wires this increase in density energy allows the use of either negative or positive polarity. Furthermore in recent studies above 50 bar it has been shown that addition of active gas does not have any significant effect on the process behaviour. In the experiments it was found that the process stability has been dominated by the high contents of He and Ar in the shielding gas. However, further experiments have to be performed to clarify this aspect.

The results obtained in the above mentioned study indicate that the parameters controlling the dynamic aspect of the process are fundamental to achieve a homogeneous and reproducable metal transfer. Three main aspects should be considered when selecting dynamic parameters for the hyperbaric GMA-Welding of duplex stainless steels:

* the current rise rate should be selected on the basis of the maximum short circuit current achieved at a given pressure. The maximum short circuit level should be as low as possible without affecting overall process stability .

* the current fall rates should be as slow as possible without compromising the overall process stability. In this way the open arc period is optimized supplying the weld pool with additional energy. This energy surplus is reflected in wider beads with low wetting angles which reduce the risk of eventual fusion defects.

* for pressures above 10 bar the shielding gas composition should be solely based on the metallurgical requirements of the weld metal. The improved arc initiation and process stability resulting from the low ionization energy of metallic oxides produced by oxygen and carbon dioxide have not been observed.

Furthermore, with the recent developments in mechanized hyperbaric welding systems, the trend seems to use the GMAW-process for filler and cap layers due to the possible higher welding speed and deposition rate. The GTAW-process will further be used for the root- and hot-passes.

Reports from experiments with the GTAW-process applied on duplex stainless steels showed slightly increased hardness values in the range of 300 HV 10 , pitting corrosion with respect to $FeCl_2$-test was fully acceptable at 20°C and could meet the specified requirements of 25°C. The ferrite/austenite phase balance could be achieved as specified to 50% / 50%.

Titanium and Titanium alloys are in progress for offshore application [29,30]. Whereas in former times this material was quite difficult to weld today immense efforts are made to develop onsite welding techniques for offshore application especially under hyperbaric dry conditions. As these materials are of a extreme corrosion and wear resistant in combination with excellent mechanical properties and strength they are very interesting for offshore application. Due to their beneficial properties long life performance and low maintenance costs can be guaranteed. The increased production rates of such materials have reduced the investment costs of such piping material to such an extent that this materials can compete with pipes from Duplex Stainless steels.

Recent development activities have been reported which try to establish a high-production welding technique: **the Plasma-MIG-process** [31] In this process the MIG arc is surrounded by a plasma sleeve generated through a second ring-shaped arc that heats an inert gas stream to extremely high temperatures up to ionization, the plasma stream. This results into a MIG arc screened by a thermally ionized gas at high temperature. Two independently controllable power sources are applied for the MIG- and the plasma-arc. High deposition rates under atmospheric conditions and in shallow depths (down to 30 mwd) under hyperbaric conditions have been successfully achieved in the as weld position (flat position). Additional experimental results mainly concentrating on the process performance and parameter settings in such shallow depths have been reported. The applicability of this process in mechanized operation to pipeline welding has to be shown. Especially positional welding (e.g. overhead, vertical) seems to be difficult to perform as the quantity of the molten material deposit is of an extreme amount. Special precautions and performance criteria in mechanized positional GMA-welding have to be observed to prepare a sound joint with high quality, the molten material deposit of the plasma-MIG-process is by far higher that a successful positional welding seems quite unrealistic. The process seems to have beneficial aspects in the preparation of cladded layers. But these are of special interest if they can be applied internally in a piping system.

Summary

The present state of hyperbaric dry welding has achieved high quality standards. The different processes as the SMAW-, the GTAW-, the GMAW- and the FCAW-process are well established and are applied in hyperbaric manual operations all over the world. Mechanized hyperbaric welding applying the GTAW-process has meanwhile even achieved reasonable acceptance. Mechanized GMA- or FCA-welding under hyperbaric conditions has been highly improved and achieved weldment qualities and performance efficiencies exceeding the so far known mechanized GTAW-processes. Further development activities for all the before mentioned processes are now concentrating more on process improvements and the application in greater water depths. Quite a large potential is still to be developed in this field..

New piping materials for offshore application require new welding processes such as the plasma welding process and new welding procedures. Apart from some preliminary investigations for its hyperbaric application these processes require further development activities especially under the mechanization aspect. Due to high voltage requirements and the existing safety regulations especially the Plasma process will probably only be applied using mechanized systems. It might benefit the processing of the new materials under hyperbaric dry conditions.

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UNDERWATER WELDING TECHNOLOGY TRANSFER

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ABSTRACT

The paper summarizes the elements considered in transferring a new technology from a military or research and development program to industrial commercial applications.

Six cutting edge technologies, of interest to the underwater welding industry, are introduced including: wet flux-core and flash but welding, portable friction stud welding, underwater thermal spraying, post weld heat treatment for wet welds and the SPINARC underwater cutting process.

INTRODUCTION

tech·nol·o·gy (tĕk-nŏl′ə-jē) *n., pl.* **tech·nol·o·gies**. *Abbr.* **technol. 1.a.** The application of science, especially to industrial or commercial objectives. **b.** The scientific method and material used to achieve a commercial or industrial objective.

trans·fer (trăns-fûr′, trăns′fər) *v.* **trans·ferred, trans·fer·ring, trans·fers**. *–tr.* **1.** To convey or cause to pass from one place, person, or thing to another.

By definition the art of technology transfer, related to underwater welding, implies transferring the applications of the science of underwater welding, to the underwater welding industry for commercial use. What the above definitions do not include is ***how*** to go about it. While there are no formal guidelines in the art of technology transfer, there are a number of key elements that must be considered to successfully transfer an application. The transfer of new and innovative technologies requires planning and the establishment of technical exchange links from research and development or military groups to manufacturing groups to distribution and support groups to the end user. Establishing these links successfully, in a free market enterprise system, for global use, requires a close look at the following elements:

1. Understanding industry needs.
2. Market analysis.
3. Tests and evaluations in compliance with industry accepted practice, national and international standards.
4. Introduction of the technology to industry.
5. Distribution of the technology
6. Support of the technology

The following paper describes the essential elements of technology transfer and introduces six technologies of interest to the underwater welding industry in various stages of transfer to commercial use in the 90's.

UNDERSTANDING INDUSTRY NEEDS

Before introducing a technology to industry, it must be determined if there is in fact a need for the application. Will the technology improve production, is it safer to use, does it stand apart from other applications currently in use, is it more cost effective, etc. If the need is established, then a market analysis is commonly used as the next step in the technology transfer process. To understand industry needs we must recognize that we are an ***international, consumer driven society*** and that consumers are effected by four environments: ***Competitive; Societal; Economic and Legal***. To meet industry needs consumer goals, problems, pressures and other related data must be assessed and carefully weighed.

MARKET ANALYSIS

A market analysis, if orchestrated correctly, will provide invaluable information needed to successfully transfer a technology to industry such as: type and number of potential markets; where are they located; the size of each existing market; market share potential; what drives the markets (industry accepted practice, standards, etc.); number of competing applications, and other crutial information. This data can be used to plan and introduce a new technology to industry.

TESTS AND EVALUATIONS IN COMPLIANCE WITH INDUSTRY ACCEPTED PRACTICE, NATIONAL AND INTERNATIONAL STANDARDS

Before introducing ~~an application to~~ industry it is recommended that a independent test and evaluation be conducted certifying that the application meets safety standards, industry accepted practice, national and international standards, regulatory requirements, underwriter requirements, environmental requirements, and other applicable criteria. Test and evaluation studies are also an effective means of demonstrating the applications ability to perform in accordance within its own published quality standards.

INTRODUCTION OF THE TECHNOLOGY TO INDUSTRY

Avenues available to introduce a new application to industry:

- Deliver informative papers on the technology to industry organizations who will benefit.
- Mail out promotional data
- Visit key industry users and demonstrate
- Sponsor test and evaluations
- Select a manufacturer with an established market base

DISTRIBUTION OF THE TECHNOLOGY

Distributors and/or manufacturers representatives are a key element in transferring technology to industry for commercial use. The following elements are of primary concern to distributors and the consumer.

- Other application options
- Quality of product
- Cost
- Delivery
- Warranty
- Flexibility
- Service / Support
- Durability
- Other related items

All of the above elements must be addressed in one form or another before industry, with few exceptions, will risk investing in and using the application for commercial use.

SUPPORT OF THE TECHNOLOGY

The underwater welding community need support and service for the applications they use. Support is generally supplied by either the manufacturer, distributor or both and should be considered as a key element of the technology transfer process.

UNDERWATER WELDING TECHNOLOGIES

The following papers (attached) introduce six state of the art technologies related to underwater welding applications in the 90's:

1. **E. O. Paton Welding Institute - "Wet Mechanized Underwater Welding with Self-Shielded Flux-Cored Wires" by Dr. Victor Kononenko**
2. **E. O. Paton Welding Institute - "Underwater Flashbutt Welding" by Dr. Kachunck Kacinko**
3. **Hydro Marine Systems - "Underwater Applications of State of the Art Portable Friction Stud Welding Equipment" by Mr. Gordon R. Blakemore and Naval Sea Systems Command - "Underwater Friction Stud Welding" by Mr. Robert Murray**
4. **GKSS - "Underwater Thermal Spraying - A Viable Alternative to Conservative Corrosion Protection Systems" by Dr. Peter Szelagowski**
5. **GKSS - "The Application of "IN SITU" Post Weld Heat Treatment to Wet Welds" by Dr. Peter Szelagowski**
6. **SPINARC, Inc. - "SPINARC Underwater Cutting Process" by Mr. Alan Krasberg**

UNDERWATER APPLICATIONS OF STATE OF THE ART PORTABLE FRICTION STUD WELDING EQUIPMENT

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KEYWORDS:

Friction welding, underwater welding, solid phase welding, damage control, salvage, anode attachment, hot-tapping, grouted clamp, friction hydro-pillar processing.

ABSTRACT

This paper outlines some of the uses of recently developed electronically controlled portable friction stud welding equipment, diver or Remotely Operated Vehicle (ROV) deployed, for underwater applications.

INTRODUCTION

Friction stud welding has been an accepted technique for use in underwater operations since the introduction of the first machine in the early 1980's.[1,2]

The ability to produce high integrity welds at considerable depth without the requirement for expensive and complex hyperbaric welding chambers has proved useful in many applications.

In the later 1980's, developments of pneumatically powered portable machines were severely hampered by the limitations imposed with large air consumption at other than very shallow depths.

Power limitations of the air machines also limited studs to a maximum size of 10mm diameter.

In 1991 HYDRO MARINE SYSTEMS designed and built the first hydraulically powered, totally instrumented and totally controlled, portable friction stud welding machine[3].

This equipment (Figure 1) is in service, and indeed is now specified by many major Oil and Gas Companies, Service Contractors and Diving Companies in the North Sea and Middle East, for welding in explosive atmospheres and underwater for a variety of different applications.

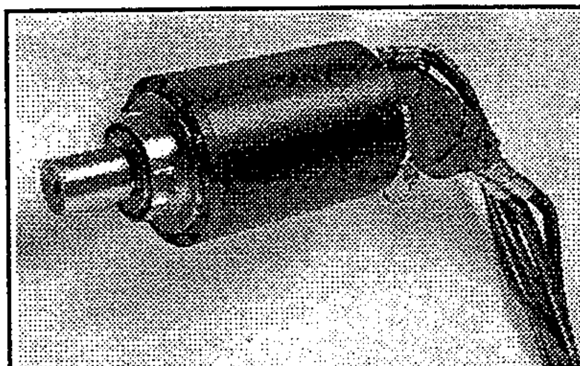


Figure 1 - HMS 3000 Weld Head

THE EQUIPMENT

All equipment is built to standards demanded by BS 5750 part 1 and ISO 9000 for quality control.

Capable of welding steel studs up to 25 mm diameter, at depths down to 1000 metres underwater, the patented control system provides a degree of control and repeatability previously unavailable in portable machines, thus removing the aspect of operator dependence which was such an important requirement of earlier machines.

Weld parameters are not only monitored, but are controlled and may be varied under full control, throughout the weld cycle.

Weld parameters are selected from the database by the operator, who may be up to 4 kilometers away from the weld site.

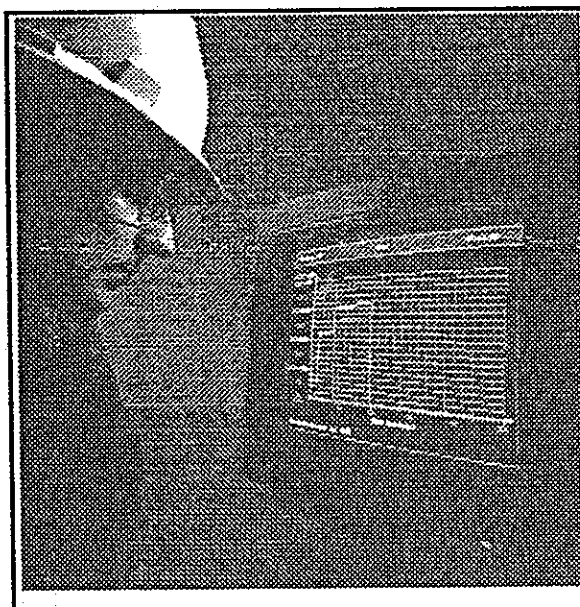


Figure 2 - HMS 3000 VDU Display

After a series of self-tests the weld is initiated by command of the Operator, and as the weld proceeds under full control, information is fed back for display in real-time on the topside Video Display Unit (VDU).(Figure 2).

VDU information is stored on disk for later hard-copy printing.

On completion of the weld the operator may then initiate the weld-test, whereby the stud is subject to a tensile proof load (normally 65% of yield) which is also shown on the VDU in real-time, and saved to disk for hard-copy printing.
Each weld record is issued a unique number by the computer system.
Provision of certificates for the stud material and base material, certified procedures by ABS, Lloyd, DNV, Bureau Veritas, and numbered prints of the VDU display for each weld and tensile test provide a complete QA/QC portfolio for the client.
In this manner, welding operations exceed the requirements of BS 6223:1990 "Specification for friction welding of joints in metal".

UNDERWATER OPERATIONS

For air-diving operations, equipment will operate through 100 metres of hydraulic umbilical from a surface Hydraulic Power Supply Unit (HPSU) and a surface control umbilical.
Deeper operations using Saturation Diving may require the use of a subsea HPSU, and a surface control umbilical.
When deployed by ROV, the welding equipment is operated from the ROV's own on-board HPSU, with control provided through the ROV umbilical.
Friction welding involves the application of considerable force during the weld cycle, which requires the use of a reaction clamping mechanism to secure the welding head.
During diver operations, the diver will place the reaction clamp and engage the weld head, after which weld control is taken by the operator.
Divers also disengage the weld head for re-loading with a new stud and foam (to prevent quench hardening) before re-locating to the next weld site.
ROV deployment may be achieved as with divers, using the ROV manipulators to reload, or (more usually) the equipment is mounted on a tool-skid which becomes an integral part of the ROV system, and includes the clamping mechanism and stud/foam reloading magazine.
In this instance the pilot will fly the ROV in and engage the clamp. Power is then switched over to the welding skid, and control passed to the friction welding operator.

CLAMPING

In workshops clamping is achieved by employing large machines similar to lathes with the facility to secure work-piece and consumable within the body of the machine.
In portable configurations this is not the case, and requires that the weld head is attached firmly to the substrate material to which the weld is to be made with sufficient security to withstand the welding forces - and at all times we have to maintain the objective of portability.
There are four main types of clamping mechanism - mechanical, electromagnetic, vacuum and hybrid (involving two mechanism e.g. vacuum and electromagnetic).

Mechanical Clamps

This constitutes the largest group of clamping devices which are very often designed for a specific task such as pipelines, tubular members (Figure 3), grating, I-beams etc..
Operation of mechanical clamps may vary from a simple manually-adjusted, manually-activated arrangement, to a sophisticated, hydraulically actuated, fully automated system for use in remote (underwater) operations.

Standard mechanical clamps are available for pipelines/tubulars from 50 mm to 2 metres in diameter.

Electromagnetic Clamps

Standard electromagnetic (Figure 4) clamps are toroidal in shape and consist of six sections, each of which will move in relation to its neighbour - thus undulating and slightly curved (minimum 3 metre radius) surfaces may be accommodated.

Vacuum Clamps

Vacuum clamps are designed for use on non-ferrous surfaces, or surfaces with thick coatings which prevent the use of magnets. These clamps may also be configured for welding to compound curved surfaces.

Hybrid Clamps

Vacuum clamps tend to be of large area to provide the required clamping force, while magnetic clamps tend to be heavy.
A hybrid vacuum/magnet clamp is smaller than a standard vacuum clamp and lighter than a magnet, for the same holding power.

APPLICATIONS

DAMAGE CONTROL

In order to secure a patch over a hole in a vessel hull two different techniques can be used.
In the first instance, where the surrounding hull material is not badly distorted, it is possible to locate studs in an accurate pattern to mate with a pre-drilled plate. Once studs are welded in place, the plate is secured over the studs sealing against the hull with a foam gasket (Figure 5).
In the second instance, where the hull material is distorted and studs cannot be placed either at regular intervals or parallel to each other, studs are placed in any convenient place around the area to be covered by the patch-plate. The plate and gasket are then placed over the hole and secured by pieces of U-

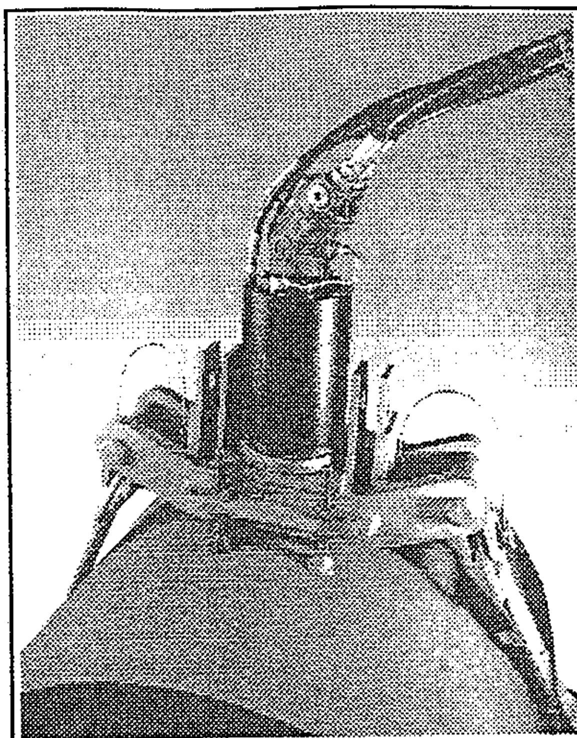


Figure 3 - Pipe/Tubular Clamp

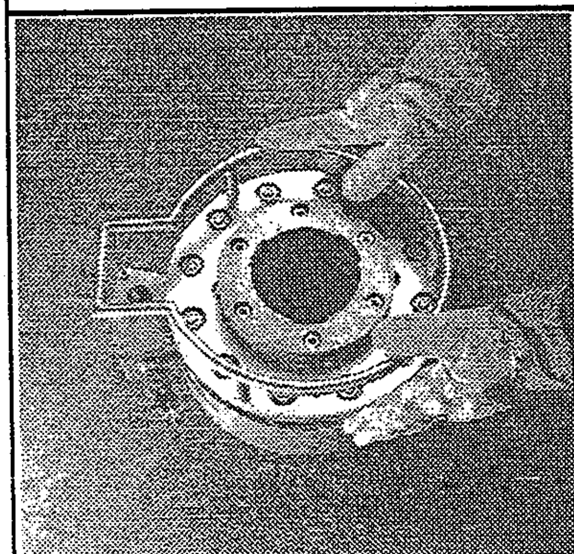


Figure 4 - Electromagnetic Clamp

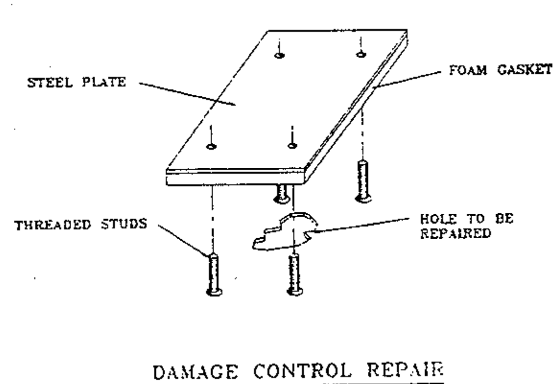
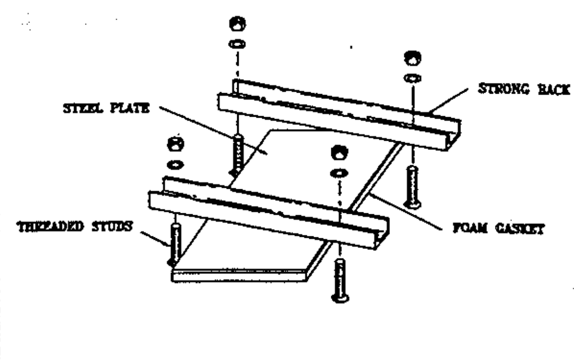


Figure 5

channel steel ("strong-backs") bolted to the studs. Holes in the U-channel may be slotted to allow for misalignment of studs (Figure 6). On completion of the patching operation, pumping out may begin. Hydrostatic effect will then assist in sealing the plate over the hole, hence the studs do not need to be large or particularly strong as they are required to locate the patch rather than act as a sealing arrangement.

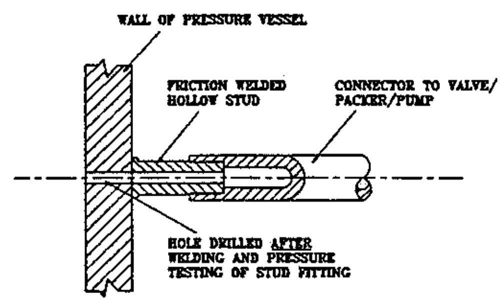


DAMAGE CONTROL REPAIR (ALTERNATIVE METHOD)

Figure 6

Hot Tapping

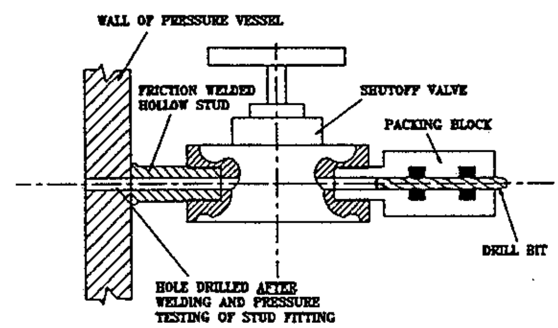
Attachment of hollow studs is completed using standard friction welding procedures, after which the hole may be continued through the substrate by passing a drill down the centre of the welded stud. This allows a connector to be screwed onto the stud to enable fluid to be pumped through the drilling (Figure 7).



HOT TAPPING OR PRESSURE CONNECTOR

Figure 7

Connections can be made to pressurised vessels by putting a valve and sealing packer onto the stud. Once the communicating hole has been drilled, the drill is withdrawn into the packer and the valve closed. The drill and packer may now be removed and the connections made before opening the valve (Figure 8).



HOT TAPPING OR PRESSURE CONNECTOR W/VALVE

Figure 8

SALVAGE

Breaches in the vessel hull are fitted with damage control patches as described above.

Hollow studs as used for hot-tapping are welded in strategic locations, and drilled through to the interior to allow connection of hoses to pump air into the vessel for lifting.

Large studs may also be welded to the vessel to allow attachment of lifting equipment such as cables or lifting bags.

ANODE ATTACHMENT

Sacrificial anodes are bolted directly to vessels or structures using threaded studs.

This has been achieved both by diver and ROV deployment to structural members of offshore structures.

In the Southern North Sea, attachments are made to gas and methanol lines for the attachment of continuity tails from 3 tonne 10 metre long anode sledges. This work is done to "live" pipelines, saving the customer between £1,000,000 and £5,000,000 per day in lost revenue which would otherwise be incurred through shut-down to allow welding to take place.

Typical resistance for studs used in electrical connections are between 20×10^{-6} and 60×10^{-6} ohms[4].

STRUCTURAL ATTACHMENTS

Numerous structural attachments have been made such as the attachment of riser clamps, installation of guides and guide-frames, mountings for structures and instruments

Grouted Clamp Repairs

Repairs to large diameter tubular members on offshore structures are often carried out using a system known as grouted clamps which consist basically of two flanged covers bolted together over the damaged area, the annulus between the tubular and the cover being pumped full of grout (concrete). To prevent movement this system has to rely on weld-beads to provide the shear resistance. Processes for welding underwater are slow, expensive and of doubtful quality which in turn means that the weld beads are difficult and expensive to put in place.

A new system has been developed and patented which uses friction welded studs to attach annular bracelets in place of weld beads to provide the shear resistance[5]. It is also possible to use friction welded studs to hold the two component halves together instead of bolts - thus the whole assembly is permanent and maintenance free as there is no requirement to re-torque bolts at given intervals.

Using this system avoids the metallurgical problems and cost implications of conventional underwater welding, while providing repeatable high quality welds faster and cheaper, with the ability to automate the process for deep water installations

Friction Hydro Pillar Processing (FHPP)

This process, patented by the Welding Institute (TWI) is the subject of a Group Sponsored Project[6] which outlines FHPP as a recently developed technique for joining and repairing thick section materials. Conventional thick section repair involves expensive consummables and lengthy processing, whilst FHPP is a low cost rapid process offering significant savings in terms of operating costs, logistics and resulting joint quality.

FHPP will be developed for use in applications such as crack repairs, welding defect repairs, and a range of joining procedures both in air and underwater for the oil, gas, power generation, shipbuilding, chemical, steel and heavy engineering sectors.

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UNDERWATER THERMAL SPRAYING - A VIABLE ALTERNATIVE TO CONSERVATIVE CORROSION PROTECTION SYSTEMS

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INTRODUCTION

High economical losses are generally caused by corrosion and wear especially on marine buildings and structures. Corrosion protection systems for such systems and offshore structures have to be designed and selected according to their protective efficiency in respect to the environmental conditions the surfaces are exposed to. A marine construction can be subdivided into three major parts in which different types of corrosion attack is acting [1].

The atmospheric zone includes that part of a construction or structure that is totally and only exposed to wind and air with at least 100% of humidity. The corrosive aggression is usually met by long lasting painted coatings. Maintenance and repair of such coatings is quite easy and does not create special difficulties.

The immersed zone is that part of a construction that is constantly immersed in the water and not at all exposed to the atmosphere. Corrosion protection is carried out for this part by cathodic protection using sacrificing anodes on the uncoated surface.

The most critical zone is the splash zone of a marine building in which tide and wave related dry and immersed periods of surface and coating are continuously alternating. During times of low water levels the previously immersed surfaces arise above the water level and dry up. They are still exposed to a high level of humidity and salt concentration of the surface and additionally to oxygen exposure, which extremely increase the corrosive attack.

Corrosion protection in the atmospheric zone is gained by long lasting paint continuously maintained and repaired. Maintenance and reinstallation of sacrificing anodes in the immersed zone is regularly performed and well established. Problems arise in the splash zone in the selection of the long lasting protection system and the mode of application itself.

The paper reports about a new system developed for such an application on the basis of the thermal spraying process serviceable in air as well as under water.

STATE OF THE ART

The exposure of offshore structures and marine constructions especially in the splash zone (Fig. 1) to chemical and mechanical attack through sea water, ice motion, collision with ship hulls, marine growth and hostile atmospheric conditions requires strong efforts to protect the surfaces thoroughly against upcoming and destructive corrosion. Since years selfcuring paint compositions that cure even under water without the influence of sunshine and oxygen have been the only protective system in this part of the structure. The life time of such coatings does not exceed more than 5 years so that continous repairs are necessary for a safe structural protection. Especially the marine growth (existing of sea pocks, shells and algae) create a severe attack to the painted coating by a strong encrustation. Such a severe encrustation starts normally immediately after the surface has been painted and builds up to a thick layer within some months only. Apart from the attack to the coating and its damage this marine growth also applies remarkable additional load to the structure so that the removal of this coverage is an essential necessity.

Different systems are available to clean the surface and prepare it for the subsequent coating. Rotating brushes, needle guns, water jet blasting with and without abrasives and underwater sand blasting systems are industrially available and well in use. The efficiency in the achievable surface cleanliness is found optimum by the two latter ones. [2] A grade of cleanliness of SA 2 1/2 minimum acc. to DIN 55 928 [3] (or SIS 05 5900-1967) is achievable and the best basis for subsequent coating. Underwater sandblasting is an especially recommended surface preparation technique for the application of underwater thermal spraying. In comparison to conventional atmospheric sandblasting modifications for underwater application are necessary. To avoid the existence of a water layer between the nozzle and the surface of the workpiece which could cause severe losses of kinetic energy of the accelerated abrasive a special nozzle has been developed to create a water free zone in this area. This nozzle guarantees the fully development of the blasting flow and kinetic energy of the grit so that an excellent surface preparation can be achieved and guaranteed. This blasting system is technically well developed and available for industrial application. It is a good preparation technique for the subsequent surface coating by thermal spray.

According to general practice and knowledge thermal sprayed coatings require an activated rough surface to guarantee good bond of the coating to the substrate. Additionally the surface has to be free from moisture and oil vapour before the coating can be applied. Therefore under atmospheric conditions these requirements are carefully maintained. In underwater application the cleaning process can be perfectly applied, the demand for a moisture free surface is not to be fulfilled as the surrounding water will immediately, after blasting, cover the cleaned surface. Accoring to general knowledge and practice this is an unacceptable situation that will prevent the coating from an acceptable bond. Generally speaking this is the reality but the hypersonic spraying system is so far the only system that provides good bond under these conditions and that is the only one that covers and fulfills the safety requirements for underwater application.

THE UNDERWATER HYPERSONIC THERMAL SPRAYING SYSTEM

The Hypersonic Spraying system is a high velocity thermal spraying system. Through a pilot flame a high energy gas stream (jet stream) from Propylene, Mapp or Hydrogen gas is generated. Powder Particles are inflated into the jet stream and heated up to melting temperature and accelerated to high velocity. The powder flow rate is controlled by Nitrogen pressure via a special regulator. The particles hit the substrate surface with high temperature and velocity and spread on the surface while rapidly cooling. The bond mechanism is generated mainly by clamping of the spreaded particles to the rough substrate surface and to a low extent by locally molten spots. This result stands entirely against usual practice and experience. However especially the high velocity of the particles in combination with the extended temperature are said to be responsible for the achieved bond strength as they destroy the moisture layer and primary oxidation on top of the surface. This is why the most important condition for underwater thermal spraying is the performance of a high energy spraying technique that provides and delivers high kinetic and sufficient thermal energy to build up a coating on the substrate's process dried surface.

In Offshore technology the underwater processes for maintenance and repair still are mainly performed manually by divers or are diver assisted processes. Because of safety reasons the use of processes, operated by high voltage such as plasma spraying systems, are prohibited. As the Hypersonic Thermal Spraying systems can be regarded as an autogeneous process, which does not require any electrical power under water [4], it seems to be the only safe process for divers in underwater application.

EXPERIMENTAL UNDERWATER FLAME SPRAYING PROCEDURE

The main emphasis on the experiments reported below was placed on the possibility of achieving a good bond between the coating and the substrate and a coating with low porosity. In extensive test series a number of experiments have been carried out in fresh water in 6 m wd [5]. The surface preparation of the steel specimens was done by the above mentioned underwater sandblasting process. As coating materials Aluminium powder 99,5 as well as Zinc powder have been selected. The grain size of the powders were -90+45 µm for the former powder and -200+100 µm for the latter one. Additional Inconel powder 625 has been applied to the same substrate with a grain size of -45+22.5µm. The spraying distance has been maintained constant at about 210 mm, the spraying time varied between 3 to 6 minutes. The pressure of the process gases was set to 8 bar. Propane was used as the main fuel gas.

The coating quality was microscopically investigated in respect to porosity, bond defects and oxide lamellae. Shading effects in the micrograph could not have been fully avoided because of extreme difficulties in the specimen preparation in the transition zone between coating and substrate. Additionally the achieved coating thickness and microhardness were measured.

RESULTS

Fig. 2 shows the metallographical cross section on an underwater flame sprayed coating of an Inconel 625 powder at a magnification of 200x. The high percentage of unmolten particles demonstrate inadequate spraying parameters. The appearance of high porosity is due to the removal of fine grained particles which have been polished away from the coating. Higher magnification of the specimen show good bonding areas although the surface preparation has been carried out in underwater sand blasting. This magnification underline the correct statement made above on the relationship between bonding and kinetic and thermal particle energy during the deposition procedure. It demonstrates that this energy is sufficient to generate the necessary bond strength between substrate and coating.

The high amount of particles polished away from the coating indicates insufficient particle temperature which may be related to insufficient treatment time in the jet stream and in consequence insufficient heating.

The achieved bond strength between the substrate and the applied Zinc coating (Fig. 3) is satisfactory. Application problems arise in the deposition of the Zinc powder as there is a high loss rate of powder due to vaporization in the jet stream. Nevertheless coating thicknesses of 80-120µm could be achieved. The application of Aluminium oxide grit as blasting abrasive shows a better anchor pattern for the deposition of the counting material.

The application of Aluminium powder as coating material was investigated as corrosion protection system. Fig. 4 demonstrates in a 1.000x magnification that a good bond is achievable in underwater thermal spraying even if the specific precautions in maintenance of the cleaned surface cannot be preserved and water has direct access to this surface immediately after sand blasting. Other micrographs even showed thicker oxide layers in the metallographical cross section of the specimens that have been coated only after a period of two hours water influence on the prepared surface has passed from the last blasting procedure. As that specimen that has immediately been coated after the cleaning procedure shows no extraordinary oxides on surface the conclusion can be drawn that the oxide layer has generated during the exposition of the cleaned surface to the surrounding water. Nevertheless good bond between substrate and coating could be recognized, tested by the chizzle test (the chizzle blade has been punched cross wise onto the coating surface).

Additional test in respect of the influence of the plasma gas on the surface roughness of the sprayed Aluminium coatings [6] presented interesting results:

A comparison between coatings produced with Propane and Hydrogen using different Aluminium powder grain sizes showed the highest surface roughness of specimens prepared with the finest grain size powder (-90+45) and hydrogen plasma gas (Ra = 46 µm). The coarser grain sizes (-150+90µm) showed a smaller difference between the two applied gases whereas the Hydrogen plasma gas produced the lowest roughness

(Ra=32,.5μm in comparison to Ra=42,5μm). These results are very important for the real application under offshore conditions. A rough surface is an ideal basis for the marine growth and should therefore be avoided.

SPECIAL SAFETY ASPECTS

The application of Hydrogen as plasma gas for underwater thermal spraying is quite expensive but not as problematic as the use of Propane gas. Hydrogen produces "clean" coatings whereas coatings with Propane may be caked with soot. Additionally a high pressure drop in the flow meters leads to recondensation which take the flow meters out of function. Therefore it is very important to provide a controlled heating device to the complete gas supply system down to the spraying gun to prevent the above mentioned condensation. Especially in underwater application this heating system is an essential necessity as the surrounding temperatures are always quite low. In this case the cooling water of the spraying gun may be used. An additional disadvantage of the propane gas is the limited operational gas pressure of 8 bar abs. which remarkably limits the application depth. Both the pressure loss in the tubing system as well as the water depths are the main components in this respect. Therefore the use of Hydrogen seems to be advantageous.

Hydrogen is a gas that has a lower density than air. In case of a leakage the gas evaporates. As it is highly inflammable in combination with oxygen special safety precautions have to be taken for the use on board of ships. Propane on the other hand has a higher density than air and sinks down. In case of the application on board of ships there exists a remarkable hazard as it may flow into lower compartment in the ship hull. Explosions can occur. Valuing all these facts Hydrogen is preferable to Propane as plasma gas even if it more expensive than the latter. Safety aspects and processing advantages speak for Hydrogen especially as the coated layers are of higher density and of more uniformity.

The application of electrically powered spraying systems such as plasma spraying or electrical are spraying provide severe hazards to the diver as their opreational electrical supply is generally not in coincidence with the international safety requirements and regulations. As the High Velocity Thermal Spraying System uses a high temperature gas stream, which will be ignited by a low powered ignition system this spraying system is the only one applicable in manned procedure. It is obvious to say that the system can even be mechanized and by this prepared as a coating system with high efficiency.

CONCLUSIONS

The experiments have demonstrated that the High Velocity Thermal Spraying Process is an applicable coasting process to prepare on site under water a suitable corrosion protection system. The results show coatings of different materials that are of high density, acceptable roughness and of good bond to the substrate. Especially the density is an important factor as no water or moisture can enter the coating and damage the bond.

Safety aspects favour the application of Hydrogen as suitable plasma gas. Limitations in the applicability are so far seen only in the length of the supply hoses and the related pressure loss to the gas supply. Further investigations in relation to life time evaluation of such coatings are still under progress.

The presented system is a promising alternative to the standard painting systems and promise a longer life time of the coating than the latter. Abrasion experiments are still due to be performed to evaluate the abrasive resistance of such coatings to mechanical attack as it is usual in the North Sea regions.

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THE APPLICATION OF "IN SITU" POST WELD HEAT TREATMENT TO WET WELDS

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1.0 INTRODUCTION

There is a substantial interest in implementing wet welding for structural repairs of offshore installations. Some of the restrictions to its use are heat affected zone (HAZ) hardening and cracking, and the inability to produce wet welds that meet the bend test requirements of a surface weld. Restrictions to the application of wet welding are even more severe in the North Sea where high strength, high carbon equivalent structural steels are used [1]. A reduction of the diffusible H_2 contents of wet welded joints (i.e. lower risk of H_2 induced cracking) would certainly lead to a re-evaluation of the process regarding its practical application, especially considering high carbon equivalent steels. This is more so in face of the acceptable mechanical properties and low defect rates achievable with some of the electrodes presently available.

Such desirable reduction in the weldments H_2 content could be achieved through an "in-situ" (underwater) post weld heat treatment (PWHT). In order to evaluate the feasibility of such heat treatment method a series of tests has been carried out in which bead-on-plate welds have been deposited on high carbon equivalent base plates and then submitted to different "in-situ" heat treatment procedures. This report presents the results of these preliminary investigations.

2.0 Theoretical Background

Due to the fast cooling rates and the high hydrogen content, characteristic of weldments produced in wet environment, hardening and cold cracking in the HAZ and weld metal are possible, especially in the case of high carbon equivalent steels (CE > 0,40%) [2].

Postweld heating methods have been investigated in order to improve the mechanical properties of underwater welds [3,4]. One way to prevent cold cracking in underwater welds is to facilitate the diffusion of atomic hydrogen by heat treating immediately after welding. Suga [3,4] investigated the effect of post-weld heat treatment on the occurrence of cracks and on the evolution process of hydrogen out of the welds using bead-on-plate runs (130mm in length) deposited underwater. After removing the slag, the test plates were immersed into an isothermal bath within 60s after completion of the welding. The test plates were kept in the bath for preset times, then cooled in water and left in air at room temperature. Suga [3,4] observed the occurrence of under bead cracks in the HAZ of underwater welds within a period of about 5 min. after welding. His observations stated that under bead cracks as well as root cracks could be prevented by "in situ" PWHT above temperatures of 100°C with appropriate holding times.

Similar results have been achieved by Ibarra et. al [5] using the multiple temper bead technique. This technique involves immediately placing a second pass over the previous one to soften the hardened HAZ and eliminate hydrogen. The experimental and practical results obtained indicated that this method was successful in assisting hydrogen diffusion out of the weldment [1].

Based on these results, a project has been devised in order to investigate specific manually operated heating processes utilizing the thermal energy of a flame stream for "in-situ" post weld heat treatment ("in-situ" PWHT) purposes. In this case, the generated thermal energy would be used to promote H_2 diffusion out of the welded joints. Another objective of the programme was to investigate the effects of the "in-situ" PWHT on the hardness of the HAZ and the weld metal.

3.0 Experimental Procedure

The test programme has been carried out in fresh water in a working pool in 6m water depth. Bead-on-plate welds have been deposited on high carbon equivalent steel plates (St 52-3, DIN 17100), followed by the application of two "in-situ" post weld heat treatment procedures. One system consists of a closed circuit cooling unit for the heating gun and a control unit, where the process parameters are set and controlled. The other system applies a hydrogen-oxygen cutting torch as heating device without any specific control units.

3.1 Materials and Consumables

St 52-3 (acc. DIN 17100) plates measuring 100x200x15mm were used as base metal. The chemical composition is presented below, out of which a Carbon-equivalent calculated according to the equation

$$CE = C + Mn/6 + (Cr+Mo+V9/5+(Ni+Cu)/15 \text{ results into } CE \cong 0.61\%:$$

ELEMENTS	CONTENT(%)
C	0,15
Si	0,4
Mn	1,3
P	0,045
S	0,035
N	<0,009
Cr	0,8
Cu	0,5
Ni	<0,4
V	0,1

Specific ferritic underwater electrodes with a rutile coating were used throughout the test programme. The bead-on-plates were deposited using 150 - 200 A. The welding voltage was at about 42V. Negative polarity (electrode negative) has been used for all specimens.

3.2 "In-situ" Post-Weld Heat Treatment

The "in-situ" PWHT procedure was performed using both systems, a modified version of the Underwater High-Velocity-Oxygen-Fuel-Thermal spraying system (Jet-heating gun) (UW-HVOF) [6] and the Hydrogen/Oxygen cutting torch. Selected parameters for the present test series as well as the respective variation range have been determined in different test series and are presented below.

PARAMETERS	VALUES
Distance between the nozzle and the test plate	50 mm and 65 mm
Oxygen-Fuel proportion	1 : 2
Treatment rate (dislocation speed of the gun along the weld bead)	1.3cm/min. and 4.0 cm/min.
Consumption of process gases	$H2 = 30\ m^3/h$ $O2 = 15\ m^3/h$

A second test series has been performed by applying an Underwater-Hydrogen/Oxygen cutting torch for Post Weld Heat Treatment. This system has been selected due to the lower gas consumption and in this respect to the financial advantages. The selected parameters are presented below.

PARAMETERS	VALUES
Distance between the nozzle and the test plate	nearly surface contact
Angle of incidence between flame and weld bead	30°
Oxygen/Fuel-proportion	1 : 2
Consumption of process gases	$H2 = 4.4\ m^3/h$ $O2 = 2.2 m^3/h$

The "in-situ" PWHT started with max. 60s after welding.

3.3 Test and Analysis

All specimens were initially submitted to metallographic analysis (macro and microscopy). Based on these evaluations a number of specimens have been selected for the following tests and analysis:

- Vickers hardness test (200g load)
- Chemical analysis
- Hydrogen determination (according to ISO 3690/77)

4.0 Results

Table 1 lists the specimens obtained in the course of the project (1.1-3.8). Also enclosed in Table 1 are the parameters and the methods of investigations used for evaluation. Additionally, reference specimens have been welded for comparison purposes.

4.1 Metallographic Evaluation

In an initial stage, the polished and unetched specimens, cut perpendicularly to the welding direction, were investigated in an optical microscope.

A detailed analysis of all specimens revealed that except the specimens 1.5 and 1.6, which presented macrocracks observed at low magnifications, i.e. 50x or 100x, all specimens 1 (reference specimen), 1.1, 1.2, 1.3, 1.4, 3.5 and 3.8 presented only microcracks, which in some cases could only be observed at a SEM. The reference specimens showed extensive cracking. As it shall be seen in item 5.0 Discussion, these cracks have apparently initiated and propagated before the "in-situ" post weld heat treatment has been applied.

Due to the "in-situ" PWHT, the HAZ area increased considerably. In several cases the solidification structure of the weld bead changes (Fig 1 and 2).

In a second stage of the evaluation, etched (2% Nital solution) specimens were investigated. Micrographs were taken from the reference and the most effectively heat treated specimen to reveal the achieved modifications in the microstructure. Different areas of the welded material were photographed at 500x magnification (Fig. 1 for the reference specimen and in Fig. 2 for the heat treated probe 1.1).

The non-treated underwater weldment showed transformed areas from a ferritic-pearlitic base material to fine grained ferrite and pearlite and further to martensite in the HAZ. An exactly shaped fusion line can be observed (Fig. 1 - A). The weld metal solidified in a dendritic structure of primary ferrite (grain boundary ferrite) and extensive areas of ferrite with aligned M-A-C (Martensite-Austenite-Carbide), and martensite (Fig.1-8/B). Spots with intergranular ferrite were also observed.

Specimen 1.1, which was post weld heat treated, shows a significantly different structure. The microstructure of the HAZ continuously changes from fine grained to coarse grained (recrystallized) ferrite and pearlite. No martensite could be observed in the coarse grained HAZ. In the weld metal, the "in-situ" PWHT procedure produced a ferritic and pearlitic structure, similar to the base material (Fig. 2).

The comparison of these metallographic results clearly demonstrates the remarkable benefits of the "in-situ" post weld heat treatment with the UW-HVOF process. An entirely different grain structure of the weld metal has been achieved which does not show any difference to the structure of the base metal.

4.2 Hardness Tests

Vickers hardness tests confirm the metallographic results. Fig. 3 shows schematically, where the Vickers identations were placed in reference to the weldment geometry.

The non-treated specimen (reference specimen) shows the commonly observed increase in hardness values from base metal through HAZ to weld metal. Fig 4 reveals these remarkable differences in hardness values between base material (about 200 HV 0,2) and HAZ (500 HV 0,2), (HV Pr.1 in the chart diagram). The path of the second curve (treated specimen, No. 1.1) demonstrates clearly that the hardness of the HAZ and the weld metal has been considerable reduced by the "in-situ" PWHT. The maximum difference in hardness values between base material and HAZ has been reduced to approximately 50 HV 0,2. The weld metal presents similar hardness values as the base metal. This effect has been achieved by moving the heating gun over the welded plate with the speed of about 1.3 cm/min with a distance between nozzle and test plate being 65 mm. Faster dislocation of the gun along the plate (i.e.: faster treatment rates) results in a different structure (HV Pr.1.2 in Fig. 5). Due to different heating and cooling conditions, the differences of hardness of the base metal and the HAZ increases between 150 HV 0,2 and 220 HV 0,2. The microstructure also shows a different transformation behaviour.

Experiments performed using different distances between the nozzle and the test plate at constant speed (Fig. 4 and 5) indicated that larger gaps produce slightly better results. Apparently, with larger gaps between the nozzle and the test plate the flame coverage area increases which influenced the cooling conditions at the test plate.

In Fig. the "in-situ" PWHT results obtained with the underwater cutting torch are compared to those achieved with the Jet-heating gun for similar gun dislocation speeds. Due to the construction and therefore the purpose of the Hydrogen/Oxygen cutting system the slowest operation speed along the weldment was 4.0 cm/min. while holding the torch under an angle of incidence of 30° to the plate surface to avoid overheating of the surface. The achieved hardness values are slightly superior to those achieved with the Jet-heating system for the same treatment rate of 4.0 cm/min. At slower speeds the Jet-heating system is superior to the previously mentioned one.

4.3 Hydrogen Tests

The influence of the post weld treatment process applied in the test series on the hydrogen contents of the weld metal is shown in Table 2 and Fig. 7. It indicates that the hydrogen content has been reduced to 35% of the reference value, depending on the parameters of the "in-situ" PWHT procedure. The best result was achieved using the Jet-heating gun with a distance between nozzle and test plate of 65 mm and a gun dislocation speed of 1.3 cm/min. which was even superior to those values revealed after heat treatment with the Hydrogen/Oxygen-torch.

4.4 Chemical Analyses

As expected, the "in-situ" PWHT has not promoted significant changes on the weld metal chemical composition (see Table 3). Nevertheless, it must be emphasized that different contents may be measured as a result of different welding conditions particularly regarding the arc length which could turn out in different degrees of oxygen absorption and therefore losses of alloying elements to the slag.

Two further reference specimens were produced and submitted to chemical analysis to determine the possible variation range in weld metal composition. The contents of some alloying elements in the weld metal were determined by chemical analysis and vary as follows:

ELEMENT	CONTENT (%)
Mn	0,47 - 0,67
Si	0,12 - 0,31
C	0,072 - 0,093
Cu	0,018 - 0,072
Ti	0,004 - 0,011

It can be argued that changes in chemical composition might occur at the weld metal surface. The metallographic analysis revealed that a thin layer (in the order of a few µm) on the weld metal surface has been heated above the melting point. Apart from that it is also possible that a limited absorption can take place at the weld metal/flame interface. However, also in this case, changes in weld metal chemical composition would be restricted to a thin layer of which the thickness is a function of the temperature distribution (i.e.: diffusion rate) at the test plate. The chemical analysis were obtained from the middle of the deposited beads. Therefore no significant changes in the weld metal chemical analysis had been achieved.

5.0 Discussion

In the "in-situ" PWHT procedure the Jet-heating gun as well as the Hydrogen-Oxygen-torch are continuously conducted along the whole weldment. Thermal energy is therefore applied for a relatively short time on each differential part of the weldment. Nevertheless, the hydrogen contents, the microstructure and hence the hardness of the weldment are substantially effected by this method.

The hydrogen content has been reduced remarkably (up to more than two thirds in comparison to the reference value). Metallographic investigations revealed an obvious change in the microstructure. The most effective "in-situ" PWHT procedure (applying the Jet-heating gun) showed fine and coarse grained ferrite-pearlite structure in the HAZ, and the weld metal itself has also been transformed into a ferrite-pearlite structure. Hardness measurements did not show any drastic increase along the weldment as it is commonly observed in conventional underwater wet welds. The Jet-heating gun process as "in-situ" PWHT procedure produced a decrease in hardness values in the order of 200 HV 0,2 to 240 HV 0,2 in the HAZ and of 180 HV 0,2 in the weld metal, as compared to the reference specimen. Hardness has been restored to base metal values.

Although two of the main elements responsible for cold cracking have been to a great extent eliminated (i.e.: reduction of the hydrogen content itself as well as the softening of weld metal and HAZ microstructure) the metallographic analysis still revealed the presence of cracks in the HAZ. Apparently the presence of cracks can be attributed to the following factors: a) the extremely high carbon equivalent of the base plant (CE ≅ 0.61%) and b) the actual time interval between bead deposition and heat treatment. The significance of high carbon equivalent to the material's susceptibility to hydrogen cold cracking is well known and does not require any explanation.

It has been shown [4] that using the multiple temper bead technique in conjunction with base metals presenting a carbon equivalent of about 0.46% a 60 seconds interval between the first weld and the tempering bead was enough to avoid hydrogen cracking. Based on these results a similar interval has been applied in the experiments performed in the present study (i.e.: 60 seconds after deposition of the test bead). It is therefore reasonable to assume that for the base plate used (CE ≅ 0.61%), shorter interval times are required. It must also be noted that with the exception of two specimens, cracks could only be detected using a SEM. This indicates that probably with minor adjustments to the heat treatment procedure crack free weldments are possible to be obtained.

6.0 Conclusion

A substantial reduction of the weldment hydrogen contents and the formation of favouable microstructures were successfully achieved with the "in-situ" UW-PWHT-procedure. The best results were achieved with the application of the Jet-heating-gun applied at a distance of 65mm between plate and torch and a dislocation speed of approximately 1,3 cm/min.

Nevertheless, as far as the practical application of the method and the related economical aspects are concerned, the "in-situ" PWHT system, still requires further investigations and constructive changes.

7.0 Literature

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Acknowledgment: The authors thank the colleagues of the Institute of Materials Science of GKSS Research Ctr., especially Mr. Schmelzer, for the evaluation of the hydrogen contents of the specimens.

Table 1 - Parameters of the UW-PWHT-test of bead-on-plate welds.

						Method of investigation				
Pr.Nr.	Method	d [mm]	t [min]	x	v [cm/min]	Macro	Micro	CA	HV	H2
1	-	-	-	-	-	x	x	x	x	x
1.1	H-G	65	15	1	1.3	x	x	x	x	x
1.2	H-G	65	5	1	4.0	x		x	x	x
1.3	H-G	50	15	1	1.3	x		x	x	x
1.4	H-G	50	5	1	4.0	x		x	x	x
1.5	H-G	50	15	3	1.3	x		x	x	
1.6	H-G	50	5	3	4.0	x		x		
3.5	H-O	<30°	5	4	4.0	x		x	x	
3.8	H-O	<30°	5	1	4.0	x		x	x	x

d – distance between the nozzle and the substrate
t – time of PWHT for one pass
x – number of passes over the weldment
H-G – Jet-Heating-gun-system (UW-HVOF-system)
H-O – Hydrogen/Oxygen-cutting system
Macro – Macrophotography
Micro – Microscopical Investigations
CA – Chemical Analyses
HV – Vickers Hardness test
< – angle of incidence between torch and weld bead

Ref.Nr.*	d [mm]	v[cm/min]	H2(diff) [µg/g]
R1	-	-	52,54
R2**	-	4	57,97
R3**	-	1,3	48,14
J-H-S			
99	50	4	30,06
102	65	4	29,18
101	50	1,3	25,15
103	65	1,3	15,50
H-O-S			
208	<30	4	38,54
207	<30	4	26,11
105	<90	4	23,28

* R1, R2 and R3 are refrence specimens which have not been subjected to "in situ" PWHT. See Figure 7 for additional information on heat treatment procedure.

/* Specimen R2 was kept 2.5min and R3 for 7.5min respectively before quenching in liquid nitrogen which corresponds to treatment velocities of 4 cm/min and 1.3 cm/min

Table 2: Content of diffusible hydrogen in the weldment of different post weld heat treated probes.

PrNr	Si/wt%/	Cr/wt%/	Mn/wt%/	Ni/wt%/	Ti/wt%/	Cu/wt%/	C/wt%/	Al/wt%/
1	0,3080	0,0005	0,4903	0,0416	0,0111	0,0328	0,0861	0,0086
1.1	0,3479	0,0006	0,5317	0,0425	0,0097	0,0272	0,1166	0,0098
1.2	0,3391	0,0007	0,5178	0,0361	0,0140	0,0514	0,1223	0,0140
1.3	0,3889	0,0007	0,6264	0,0390	0,0099	0,0487	0,0973	0,0116
1.4	0,4153	0,0005	0,6293	0,0417	0,0112	0,0080	0,0828	0,0096
1.5	0,4555	0,0010	0,5090	0,0056	0,1000	0,0104	0,1529	0,0132
3.5	0,1647	0,0241	0,4453	0,0000	0,0049	0,0084	0,0828	0,0060
3.8	0,1873	0,0014	0,4735	0,0000	0,0073	0,0089	0,0863	0,0062

Table3: Chemical Analysis of the different heat treated weldments

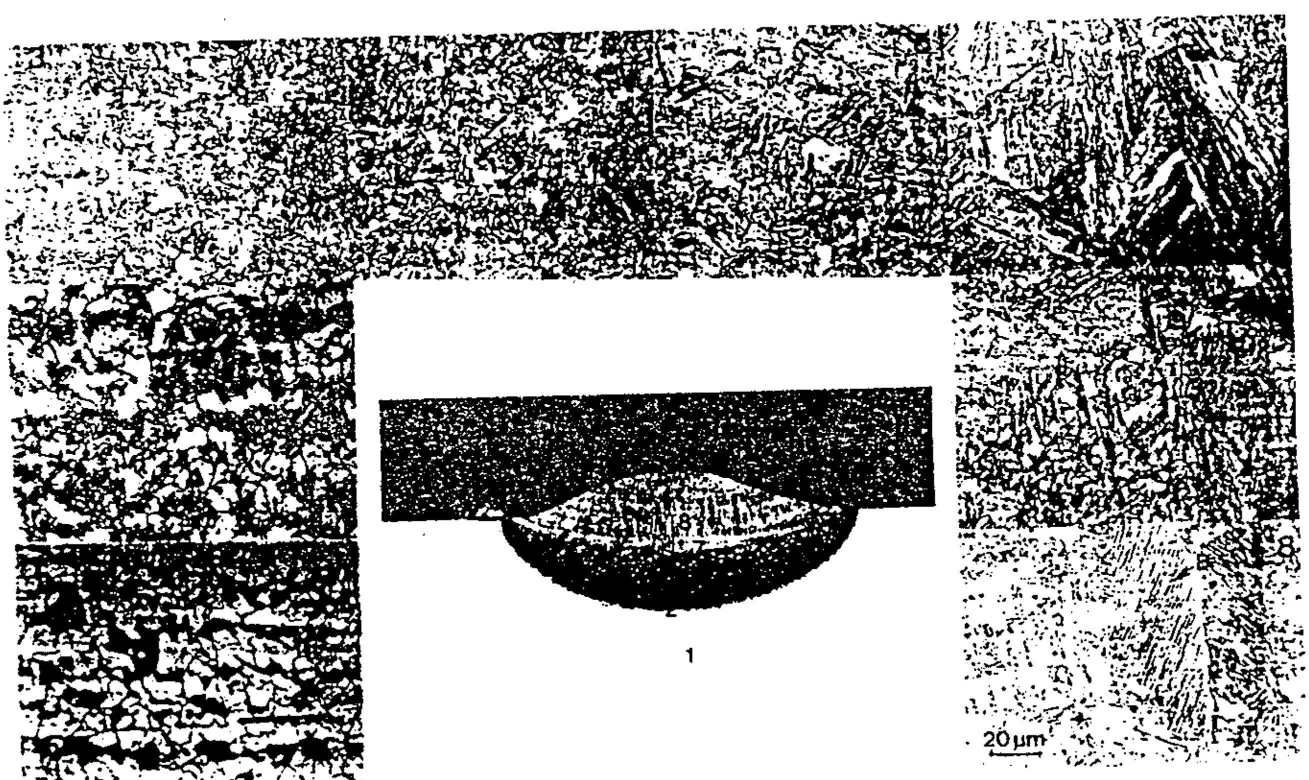

Fig. 1: Micrograph of the reference specimen Nr. 1, not heat treated, 7 x and 500 x magnification

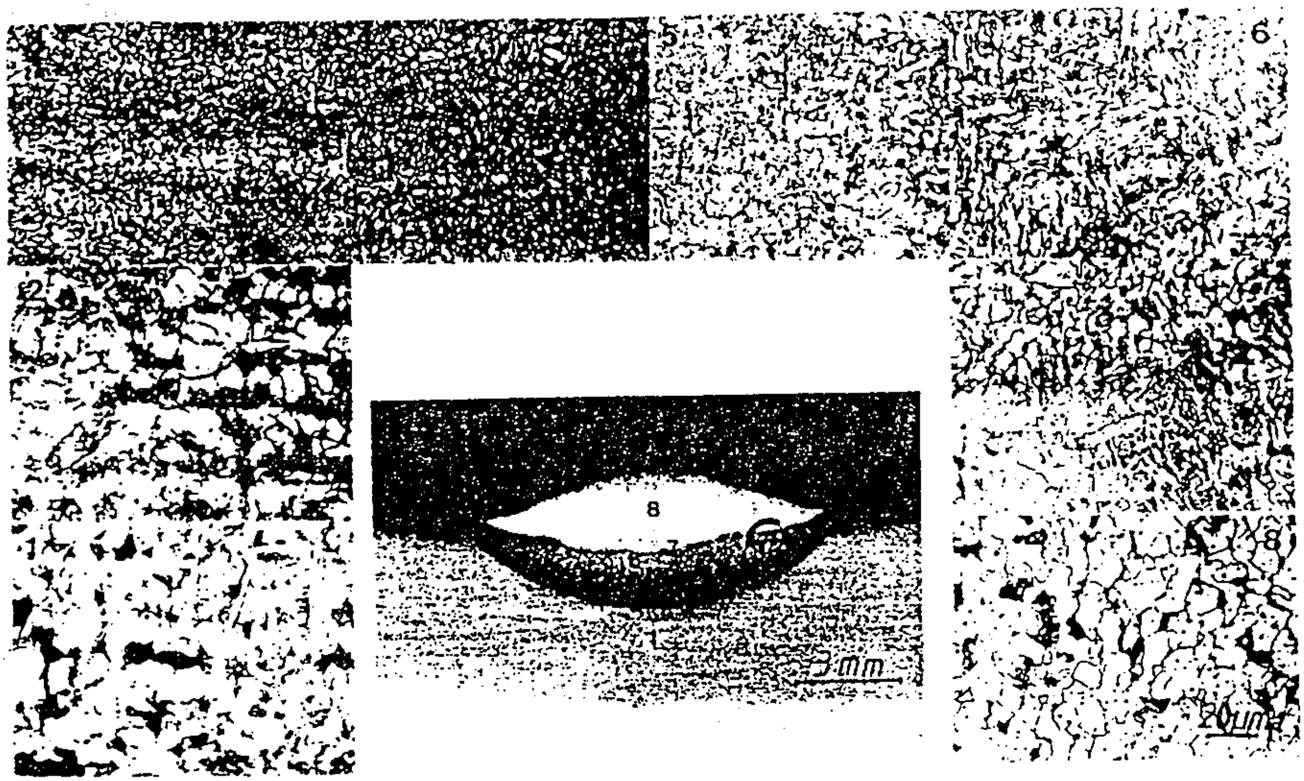

Fig. 2: Micrograph of the UW-PWHT specimen Nr. 1.1, 7 x and 500 x magnification

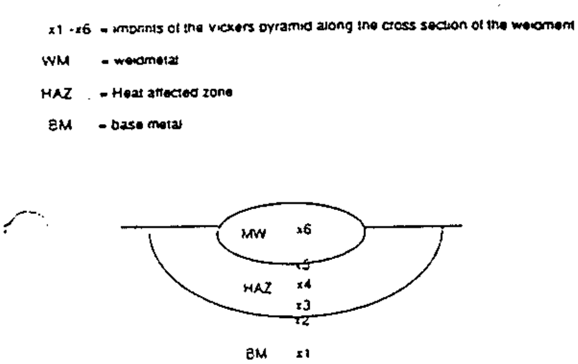

Fig. 3: Scheme of imprints of the Vicker's pyramid in the cross section of the weldment

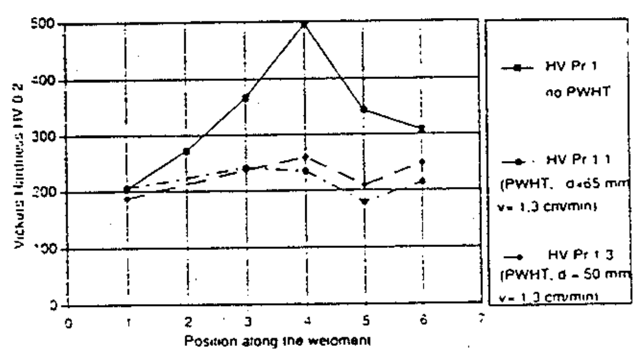

Fig.4: Vicker's Hardness in bead-on-plate weldments achieved with constant PWHT-speed and different nozzle distances

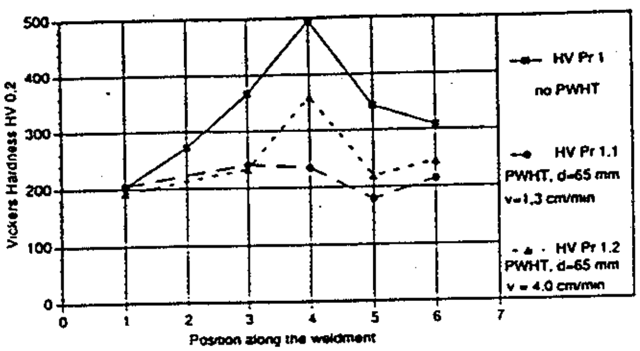

Fig. 5: Vicker's Hardness in bead-on-plate weldments with differnt PWHT-speed and constant nozzle distance

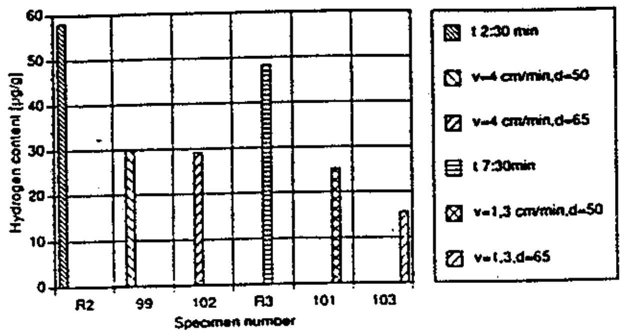

Fig. 7: Content of diffusable Hydrogen in bead-on-plat welds with PWHT applying the Jet-Heating process

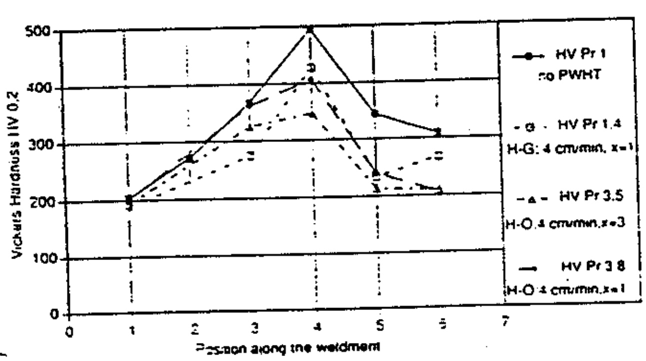

Fig. 6: Achievable Hardness values with the two different PWHT-processes

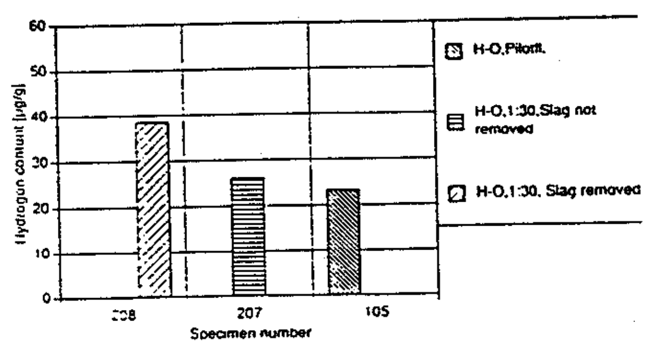

Fig. 8: Content of diffusable Hydrogen in bead-on-plate wieds with PWHT applying the Hydrogen-Oxygen-torch

SPINARC UNDERWATER CUTTING PROCESS

Alan Krasberg - SPINARC, INC.

Spinarc is a novel method for underwater cutting of metals or other electrical conductors. It is a cousin to the EDM or spark erosion process. Spinarc is faster and cheaper to operate (electrodes last much longer) but does not produce as good a finish. It can serve as a substitute for EDM for roughing out of very large parts. Spinarc has been under development for about three years, but significant break-throughs have been achieved only in the last six months. To protect proprietary interests, the discussion of the process will be limited to process capabilities.

Spinarc is being developed for in situ cutting of decommissioned nuclear reactor pressure vessels. It also has possible applications in industrial and manufacturing processes, and is a candidate for use in the decommissioning of reactor vessels and missiles in scuttled nuclear submarines. It is estimated that approximately 200 land-based nuclear power plants are awaiting decommissioning in addition to some 200 (mostly Soviet) scuttled submarines.

The process works over a wide pressure range, has a long tool life, and produces clean and dependable automated cuts. The primary forces exerted on the tool are caused by water jets and the magnetic fields generated by the process. The forces involved are low enough to allow lightweight, near neutral-buoyancy tool construction. The tool will be ROV-handleable, and provided a 250 kg transformer can be carried on the ROV, no umbilical or other services would be required. Spinarc is an electrical process that uses no oxygen, so little actual "burning" takes place. The amount of electrolytic oxygen generated decreases with increasing depth, and no visible bubbles are generated beyond 800 MSW.

The basic tool can be held by an ROV manipulator for most simple jobs. Larger or more intricate cuts in H-beam, pipelines, wire rope, anchor chain, or wreckage may require that the tool be incorporated in a light-weight ready-to-use package that can be positioned by a diver or an ROV. The cutting forces are sufficiently low to allow magnetic attachment of the tool to the workpiece.

Cutting speed is a non-linear function of available power. A typical ROV that can provide for peak power of 10 kW (5 kW average power) will allow cutting rates in 1/2" steel of 20-30 cm per minute. Doubling the power roughly quadruples the cutting speed. Slow cutting speeds resulting from low available power will usually be offset by time savings due to the simplicity of the setup. Special positioning jigs are required only if very precise positioning is needed.

The Spinarc electrode does not physically contact the workpiece during cutting. Workpiece-to-electrode wear ratios are in excess of 1000 to 1. This is approximately 20 times better than the best wear rations achieved by EDM processes, and is reflected in the long life of electrodes. Spinarc has been tested successfully to simulated depths of 6000 MSW. The finish of the cut surface improves with increasing pressure.

UNDERWATER FRICTION STUD WELDING[1]

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ABSTRACT

The Naval Sea Systems Command (NAVSEA), Director of Ocean Engineering, Underwater Ship Husbandry Division (NAVSEA 00C5) initiated a program for underwater friction stud welding in June of 1992. A test plan was derived to provide a comparison between welds made underwater to those made on the surface. All welding and testing was performed under the guidance of MIL-STD-1689 and MIL-STD-248.

Variables of the testing required welding test plates in the vertical and overhead position in water temperatures of 65°F and 32°F, and at water depths of 32 ft and 1 ft. A set of weldments were also produced in air at ambient temperature to establish a base line for comparison with the wet weldments. Weldments were made using 12mm and 25mm carbon steel studs against 1-inch thick DH-36 and HY-80 base plates.

The successful result of this program has enhanced the Navy's underwater ship husbandry capabilities by providing a means of performing such tasks as zinc anode attachments, external blanking of sea chests for ship deactivation, and temporary attachment points for rigging, tasks which previously required qualified traditional underwater stick welders.

INTRODUCTION

The friction welding process has been used for centuries in the form of forging as a method of joining metals. The process as we know it today was patented in the 1890's and utilized large machines which required enormous power supplies. It was not until the mid 1980's that the size of the machines were reduced when the first portable underwater friction stud welder was introduced for work in the North Sea.

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[1] Approved for Public Release
Distribution Unlimited

Friction welding is considered a solid state process as no melting of material occurs. The weldment never exceeds the plastic state and the weld is formed by applying a compressive load while the weldment remains in the plastic state. A bond is created by super-cleaning, followed by an interchange of ions across the interface of the weldment. Therefore, no fusion zone is created and the Heat Affected Zone (HAZ) is small. As a result of this process, the weld strength is equal to or greater than the base material. Problems from inclusions and porosity are eliminated since there is no liquid state during the friction process. The compressive loading used in the process also tends to eliminate stress corrosion cracking by refining the grain structure within the HAZ.

WELDING OF TEST COUPONS

Pnuematic and hydraulic powered friction stud welders were used to produce the 214 weldments required by the test matrix shown in table 1. All of the underwater welds were effected by using a closed cell foam collar made from Expanded Vinyl Acetate around the stud prior to welding. This was necessary to insulate the weldment from cold quenching effects of the surrounding water. During the friction process, the physical pressure of the foam collar prevents water from contacting the stud and as the process progresses through its cycle, the hot plasticised metal flows into the collar causing it to melt and release an inert gas while forming a hollow chamber. It should be noted that the studs could easily be welded through the light coat of primer paint on the HY-80 coupons, however, the mill scale on the DH-36 coupons had to be removed prior to welding.

COUPON TESTING

The following tests were conducted to evaluate the quality of the friction weldments made from both HY-80 and DH-36 produced under the various combinations of ambient temperature, water depth and positions as outlined in Table 1:

- Chemical analysis
- Torque tests
- Torque/bend tests followed by metallographic examination to asses
    - Existence of linear indications in the weld zone
    - HAZ hardness
    - HAZ microstructures
    - Charpy V-notch impact tests

EVALUATION

Tables 2 through 7 compile all the results of testing. In summary, the series of mechanical property tests consisting of torque tests, combination torque/bend tests followed by detailed metallographic examination and Charpy V-notch impact tests were performed to evaluate the quality of friction stud welds made on both HY-80 and DH-36 material and welded under various combinations of ambient temperature, water depth, and position. The chemical analysis demonstrates that these results are conservatively applicable to friction stud welding of carbon steel studs having a chemistry equivalent to ASTM A36 to base plates of HY-80 and DH-36 having properties as specified by MIL-S-16216 and MIL-S-22698, respectively. None of the environmental, attitude, and material variables had a significant impact on the mechanical properties of the weldments, which met or exceeded the requirements for fusion welded studs as specified by MIL-STD-1689 and MIL-STD-248.

CONCLUSIONS

Qualification of Navy divers for underwater welding has been, for many years, a difficult task to achieve. The stringent but needed requirements of the Naval Ships Technical Manual Chapter 074 - Volume 1 which assures quality and top workmanship for all ship repair has deterred many Navy activities from pursuing qualifications. Friction stud welding, being somewhat autonomous, requires the majority of the qualification effort to be placed on the equipment and not the welder. The welder actually becomes an operator requiring minimal training and qualification. This has allowed activities such as Norfolk Naval Shipyard to successfully perform underwater weld repairs which included anode attachments, underwater tug boat fender replacement, and submarine stern plane marker installations with minimal training and incurred cost.

ACKNOWLEDGMENT

The work described in this report are the results of NAVSEA tasks awarded to Battelle Memorial Institute for generating and executing the test plan and Edison Welding Institute for testing and evaluation of final weldments. Technical support was also given by NAVSEA code 03M2, Naval Surface Warfare Center, Carderock Division, code 623B, and Welding Engineering Services, Third Party Plus.

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TABLE 1. STUD WELDING TEST MATRIX

TEST	SPECIMEN NUMBER	STUD DIAMETER	BASE MATERIAL	WELD POSITION	NUMBER OF SPECIMENS	WELD DEPTH feet	AMBIENT TEMP. degrees F	NOTCH LOCATION
Charpy Impact		1 in.	HY-80	vertical-5F	3	32	65	HAZ (base)
		1 in.	HY-80	vertical-5F	3	32	65	FL
		1 in.	DH36	vertical-5F	3	32	65	HAZ (base)
		1 in.	DH36	vertical-5F	3	32	65	HAZ (stud)
		1 in.	DH36	vertical-5F	3	32	65	FL
		1 in.	HY-80	vertical-5F	3	(in air)	(room)	HAZ (base)
		1 in.	HY-80	vertical-5F	3	(in air)	(room)	FL
		1 in.	DH36	vertical-5F	3	(in air)	(room)	HAZ (base)
		1 in.	DH36	vertical-5F	3	(in air)	(room)	HAZ (stud)
		1 in.	DH36	vertical-5F	3	(in air)	(room)	FL
		1 in.	HY-80	vertical-5F	3	1	32	HAZ (base)
		1 in.	HY-80	vertical-5F	3	1	32	FL
		1 in.	DH36	vertical-5F	3	1	32	HAZ (base)
		1 in.	DH36	vertical-5F	3	1	32	HAZ (stud)
		1 in.	DH36	vertical-5F	3	1	32	FL
		(no stud)	DH36	n/a	3	n/a	n/a	plate
		(no stud)	HY-80	n/a	3	n/a	n/a	plate
		1 in.	(no base)	n/a	3	n/a	n/a	stud
				Total Charpy Specimens	54			
Torque	1 - 5	12 mm	DH36	overhead-4F	5	32	65	n/a
	6 - 20	12 mm	DH36	vertical-5F	15	32	65	n/a
	201 - 205	12 mm	HY-80	overhead-4F	5	32	65	n/a
	206 - 220	12 mm	HY-80	vertical-5F	15	32	65	n/a
	21 - 25	12 mm	DH36	overhead-4F	5	1	32	n/a
	26 - 30	12 mm	DH36	vertical-5F	5	1	32	n/a
	221 - 225	12 mm	HY-80	overhead-4F	5	1	32	n/a
	226 - 230	12 mm	HY-80	vertical-5F	5	1	32	n/a
				Total Torque Specimens	60			

TABLE 1. STUD WELDING TEST MATRIX (Continued)

TEST	SPECIMEN NUMBER	STUD DIAMETER	BASE MATERIAL	WELD POSITION	NUMBER OF SPECIMENS	WELD DEPTH feet	AMBIENT TEMP. degrees F
Torque/Bend	31 - 32	12 mm	DH36	overhead-4F	2	32	65
	33 - 34	12 mm	DH36	vertical-5F	2	32	65
	231 - 235	12 mm	HY-80	overhead-4F	5	32	65
	236 - 240	12 mm	HY-80	vertical-5F	5	32	65
	35 - 36	12 mm	DH36	vertical-5F	2	1	32
	241 - 242	12 mm	HY-80	vertical-5F	2	1	32
	37	12 mm	DH36	vertical-5F	1	(in air)	(room)
	243	12 mm	HY-80	vertical-5F	1	(in air)	(room)
				Total Torque/Bend Specimens	20		
Tensile (stud only)		12 mm	n/a	n/a	1	n/a	n/a
		1 in.	n/a	n/a	1	n/a	n/a
				Total Tensile Specimens	2		
Chemical Analysis		n/a	DH36	n/a	1	n/a	n/a
		n/a	HY-80	n/a	1	n/a	n/a
				Total Chemical Analysis	2		
				TOTAL SPECIMENS	138		

* No hardness traverses on these specimens.

TABLE 2. CHEMICAL COMPOSITION OF THE BASE MATERIALS AND STUDS

Element	HY-80		DH-36		Studs	
	Sample	MIL-S-16216K(SH) Specification	Sample	ABS Rules or ASTM A131 Specification	12mm Diameter	1-inch Diameter
C	0.12	0.12 - 0.18	0.23	0.18 max	0.16	0.17
Mn	0.31	0.10 - 0.40	1.03	0.90 - 1.60	0.37	0.73
P	0.007	0.015 max	0.014	0.035 max	0.007	0.014
S	0.004	0.008 max	0.006	0.04 max	0.010	0.017
Si	0.20	0.15 - 0.38	0.29	0.10 - 0.50	0.058	0.22
Ni	2.13	2.00 - 3.25	0.29	0.40 max	0.018	0.048
Cr	1.14	1.00 - 1.80	1.14	0.25 max	0.042	0.063
Mo	0.25	0.20 - 0.60	0.007	0.08 max	0.029	0.017
V	0.005	0.03 max	0.005	0.10 max	0.001	0.000
Ti	0.001	0.02 max	0.001	---	0.001	0.001
Cu	0.13	0.025 max	0.007	0.35 max	0.010	0.10
Sb		0.025 max		---		
As		0.025 max		---		
Sn	0.008	0.030 max	0.002	---	0.001	0.005
Nb	0.000	---	0.000	0.05 max	0.000	0.000

TABLE 3. RESULTS OF TORQUE TESTS ON 12-mm-DIAMETER STUDS

Plate Material	Ambient Temperature (°F)	Water Depth (ft)	Welding Position	Specimen No.	Torque at Break (ft-lbs) Individual Values	Average	Standard Deviation
HY-80	65	32	Overhead-4F	201-205	85, 60, 60, 60, 60	65	10
			Vertical-5F	206-220	60, 70, 70, 65, 70, 65, 70, 70, 75, 60, 70, 80, 70, 80, 70	70	5
	32	1	Overhead-4F	221-225	75, 65, 65, 65, 60	65	5
			Vertical-5F	226-230	85, 65, 70, 70, 60	70	10
DH-36	65	32	Overhead-4F	1-5	70, 70, 65, 70, 65	70	5
			Vertical-5F	6-20	70, 70, 65, 70, 65, 65, 60, 55, 60, 70, 95*, 65, 70, 70, 65	65	5
	32	1	Overhead-4F	21-25	70, 70, 65, 65, 65	70	5
			Vertical-5F	26-30	60, 70, 60, 75, 65	65	5

NOTES:

(1) Per MIL-S-1689A Section 6.9.2, required torque at break is for a 12mm diameter UNC stud is at least 44 ft-lbs if failure occurs in the weld or at least 39.6 ft-lbs if failure occurs in the stud.
(2) All breaks occurred in the threaded region of the stud.
(3) Individual test results are ordered by ascending specimen number.
(4) Readings average to quoted value ±2.5 ft-lbs. Averages and standard deviations are reported to the nearest even 5 ft-lbs.
(5) Individual values marked with a * indicate that no lubrication was used. These values were omitted from calculation of the average.

TABLE 4. SUMMARY OF LINEAR INDICATIONS DETERMINED FROM 7X PHOTOGRAPHS OF SECTIONED 12mm STUDS

Base Material	Ambient Temperature (°F)	Water Depth (ft)	Welding Position	Specimen No.	Section Orientation to RD	Left Side Length (in.)	Left Side Type	Right Side Length (in.)	Right Side Type	Accept / Reject (a)
HY-80	65	32	Overhead-4F	231	Transverse	0.0450	Linear	0.0731	Linear	Reject
				232	Longitudinal	0.0000	None	0.0562	Linear	Accept
				233	Longitudinal	0.0619	Linear	0.0675	Linear	Reject
				234	Longitudinal	0.0562	Rounded	0.0056	Linear	Accept
				235	Longitudinal	0.0675	Rounded	0.0731	Linear	Reject
			Vertical-5F	236	Transverse	0.0450	Linear	0.0731	Rounded	Reject
				237	Longitudinal	0.0619	Linear	0.0112	Notch	Accept
				238	Longitudinal	0.0619	Linear	0.0675	Linear	Reject
				239	Longitudinal	0.0450	Rounded	0.0506	Rounded	Accept
				240	Longitudinal	0.0450	Linear	0.0619	Rounded	Accept
	32	1		241	Transverse	0.0844	Linear	0.0394	Linear	Reject
				242	Longitudinal	0.0112	Linear	0.0337	Linear	Accept
	Room	Air		243	Transverse	0.0225	Linear	0.0450	Linear	Accept
DH-36	65	32	Overhead-4F	31	Transverse	0.0000	None	0.0141	Rounded	Accept
				32	Longitudinal	0.0844	Linear	0.0562	Linear	Reject
			Vertical-5F	33	Transverse	0.0056	Notch	0.0394	Linear	Accept
				34	Longitudinal	0.0394	Rounded	0.0000	None	Accept
	32	1		35	Transverse	0.0731	Linear	0.0619	Linear	Reject
				36	Longitudinal	0.0112	Linear	0.0450	Linear	Accept
	Room	Air		37	Transverse	0.0056	Linear	0.0450	Rounded	Accept

(a) Acceptability judged relative to the MIL-STD-248D Section 4.4.5.1(c) for load-bearing fusion-welded studs which rejects all indications exceeding 1/16-in. in length. All indications were in the residual flash material resulting from improper welding force.

TABLE 5. SUMMARY OF MICROHARDNESS DATA FROM THE SECTIONED 12mm STUDS

Base Material	Ambient Temperature (F)	Water Depth (ft)	Welding Position	Specimen No.	Section Orientation to RD	Hardness Values						
						Stud Avg (VHN)	Plate Avg (VHN)	Stud HAZ Max (VHN)	Plate Max (VHN)	Maximum Base to HAZ Deviation		
										(VHN)	(approx ksi)	Location
HY 80	65	32	Overhead - 4F	231	Transverse	176	250	225	429	179	89	Plate
				232	Longitudinal	176	252	218	448	196	99	Plate
			Vertical - 5F	236	Transverse	172	246	208	438	192	96	Plate
				237	Longitudinal	171	247	225	429	182	91	Plate
	32	1		241	Transverse	174	243	226	424	181	90	Plate
				242	Longitudinal	168	239	223	463	224	113	Plate
	Room	Air		243	Transverse	160	239	240	408	169	83	Plate
					Longitudinal	180	239	253	424	185	92	Plate
DH 36	65	32	Overhead - 4F	31	Transverse	170	184	228	453	269	131	Plate
				32	Longitudinal	173	179	216	429	250	120	Plate
			Vertical - 5F	33	Transverse	171	199	218	415	216	104	Plate
				34	Longitudinal	170	199	225	411	213	102	Plate
	32	1		35	Transverse	168	187	210	468	281	138	Plate
				36	Longitudinal	166	187	219	463	276	136	Plate
	Room	Air		37	Transverse	169	184	198	398	214	102	Plate
					Longitudinal	169	184	183	398	214	101	Plate

(a) Vicker's hardness number (VHN) measured as per ASTM E384-89 using 0.5 kg load and a 15 second hold time.
(b) Approximate tensile strength was calculated using an correlation for steels found in ASTM A370-92.

TABLE 6. MAXIMUM AND MINIMUM GRAIN SIZES OF THE SECTIONED 12 mm STUDS

Base Material	Ambient Temperature (°F)	Water Depth (ft)	Welding Position	Specimen No.	Microstructure - ASTM Grain Sizes			
					Largest Grain Size	Largest Location	Smallest Grain Size	Smallest Location
HY-80	65	32	Overhead-4F	232	5	Stud HAZ	10	Plate HAZ
			Vertical-5F	237	5	Stud HAZ	10	Plate HAZ
	32	1		242	5	Stud HAZ	10	Plate HAZ
	Room	Air		243	5	Plate HAZ	10	Plate HAZ
DH-36	65	32	Overhead-4F	32	5	Stud & Plate HAZ	10	Plate HAZ
			Vertical-5F	34	5	Plate HAZ	10	Plate HAZ
	32	1		36	5	Plate HAZ	10	Plate HAZ
	Room	Air		37	5	Plate HAZ	10	Plate HAZ

NOTES:

(1) Stud grain size is ASTM 8
(2) HY-80 grain size is ASTM 7
(3) DH-36 grain size is ASTM 9
(4) All sections are longitudinal to the plate rolling direction.
(5) Prior austenite grain sizes were measured using the line intercept method outlined by ASTM E112-88.

TABLE 7. CHARPY V-NOTCH ENERGIES FOR SAMPLES REMOVED FROM THE 1-INCH STUDS AND TESTED AT 0 °F

Base Material	Notch Location	Ambient Temperature (°F)	Water Depth (ft)	Specimen Nos.	CVN Energies (ft-lbs)(a)				Distance from Notch Root to Fusion Line (in.)		
					V1	V2	V3	Avg.	V1	V2	V3
	Base	N/A	N/A	262-264	76	94	54	75			
HY-80	HAZ Base	65	32	244-246	6	28(b)	10	15	0.020	0.051	0.028
		1	32	256-258	26(b)	18(b)	30(b)	25	0.049	0.037	0.032
		Room	Air	250-252	32(b)	11	6	16	0.055	0.031	0.024
	Fusion Line	65	32	247-249	5	8	7	7			
		1	32	259-261	6	5	6	6			
		Room	Air	253-255	6	4	5	5			
	Stud	N/A	N/A	N/A	6	4	4	5			
DH-36	Base	N/A	N/A	66,68,71	52	46	72	57			
	HAZ Base	65	32	38-40	6(c)	6	6	6	0.037	0.042	0.039
		1	32	56-58	6	6	6	6	0.027	0.035	0.034
		Room	Air	47-49	7	7	9	8	0.036	0.034	0.027
	Fusion Line	65	32	44-46	7	9	5	7			
		1	32	62-64	3	5	4	4			
		Room	Air	53-55	4	5	5	5			
	HAZ Stud	65	32	41-43	6	9	8	8	0.054	0.059	0.054
		1	32	59-61	5	9	12	9	0.039	0.067	0.067
		Room	Air	50-52	7	124(d)	4	6	0.051	0.081	0.028
	Stud	N/A	N/A	N/A	6	4	4	5			

(a) Individual energy values are listed in order of ascending specimen number.
(b) Energy values elevated because crack jumped laterally from notch to fusion line before propagating.
(c) Specimen No. 69 replaces No. 38. Welded at 12 ft rather than at 32 ft.
(d) Off-center impact. Energy value invalid and, therefore, not included in average.
(e) All welds made in the vertical (5F) position.

APPLICATION OF RESISTANCE FLASH-BUTT WELDING IN CONSTRUCTION OF OFF-SHORE PLATFORMS AND UNDERWATER PIPELINES

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ABSTRACT

The technology and equipment for resistance flash-butt welding of 50 mm to 1420 mm diameter pipes developed by the E.O. Paton Electric Welding Institute has been for many years extensively used in the CIS countries in the construction of various types of pipelines.

The technology has been developed lately for welding up to 1600 mm diameter pipes with up to 60 mm wall thickness, providing quality welding at two times lower power than in the previous generation of machines. It has allowed the development of specialized welding equipment, which welds thick-walled pipes in 8 to 10 minutes when lowering piles, it significantly improving the efficiency of welding work performance. The design of a specialized machine for welding piles of 1220 mm diameter with up to 30 mm wall thickness was developed.

The performed studies have shown the capability of carrying out resistance flash-butt welding in a local chamber built into the clamps of a conventional pipe welding machine. The quality of joints on various pipes was studied under up to 3.5 MPa pressure of gas in the chamber, it corresponding to the water depth of up to 350 m. The resistance flash-butt welding of pipes of 219 mm diameter was performed in a specially modified machine under water at up to 60 m depth. Test samples of pipes of X52, X65 steel were welded, which were subjected to comprehensive mechanical tests. The welded joint quality corresponded to API requirements. Underwater welding of off-shore industrial pipelines was performed, and possible sequences of work performance when using such a technology were determined.

INTRODUCTION

The resistance flash-butt welding of pipes is extensively used in CIS countries in construction of various on-land pipelines ranging in diameter from 57 up to 1420 millimeters. More than 70,000 km of various pipelines have been welded by this process, all of them operating smoothly. Over the entire service period there were no cases of failure of the butts welded by the method.

The advantages of this welding method, namely high efficiency, capability of complete automation of the process stable and high joint quality, make this technology quite attractive also for other applications, in particular, for construction of off-shore structures where joining of pipe butts is also required.

RESISTANCE FLASH-BUTT WELDING OF PLATFORM PILES

One of the applications where, in our opinion, the resistance flash-butt welding of pipes can be used quite effectively, is welding of circumferential butts of thick-walled pipes in incremental building of off-shore platform piles. When constructing deep-sea platforms, a pile is lowered inside the main vertical column along its entire length, see Fig. 1, which is driven into the ground. The piles are usually made of incrementally thick-walled pipes of up to 1600 mm diameter. Such an operation is now performed by the processes of electric arc, manual or mechanized welding and takes many hours during which all the other equipment, in particular, powerful floating cranes, is idle. Therefore, finding methods of improving the efficiency of welding circumferential welds is a quite urgent task. The application of resistance welding in this case would permit to markedly increase the welding efficiency, reduce the welding time to 400-600 s, instead of 5 - 8 hours with the conventional method. However, a number of complex engineering tasks have to be solved. At present there is experience of production welding up to 1420 mm diameter pipes with 20 - 22 mm wall thickness. Here, standard mobile electric power stations of up to 1,000 kW power and welding machines of up to 20,000 - 25,000 kg weight are used. In pile welding the cross-section area of the pipes may exceed the mentioned sections several times. Therefore, it became necessary to develop a technology to provide quality welding at lower specific powers. It is also quite urgent to find ways of lowering the required specific pressures and upsetting forces of welding machines, respectively, as well as reducing the amount of the flash formed.

The investigations demonstrated the possibility of making sound joints at specific powers of 5 - 6 VA/mm^2, it being about twice lower, than in the existing equipment in welding 1420 mm pipes. The metal losses in welding have also been reduced, they being equal to 20 - 30 mm, and those for upsetting are equal up to 10 mm, see Table 1.

Table 1 Main data on welding

Pipe dimensions, mm	Welding time, s	Welding power, kW	Upset force, MN	Flashing displacement, mm	Upset displacement, mm
D = 1220 δ = 30	300	1000	3.5	15	8
D = 1 620* δ = 60	600	2000	10.0	25	10

* The data were calculated from results of welding the plates of 20,000 mm cross section cut out of pipes

As can be seen from the macrosection in Fig. 2, the weld reinforcement is just 5 - 6 mm, removal of the inner and outer flash not being required in many cases. Mechanical properties of joints are given in Table 2. Tests were performed in keeping with API standard. The level of properties meets the specified requirements. As can be seen from Table 1, the power consumed in welding 1220 mm diameter pipes with 30 mm wall thickness is equal to 1000 kW. When a special converter is used for supplying power to the welding machine, a standard three-phase power source will be required. In many cases it is possible to supply power from the power network of the floating crane which installs the piles.

Table 2 Results of mechanical testing*

Pipe dimensions, mm	Steel grade	Yield strength, MPa		Tensile strength, MPa		Impact energy J, +20 °C
		PM	WM	PM	WM	
D = 1220 δ = 30	Ст20	320	310	512	567	42
D = 1620 δ = 60	Ст3	220	210	420	422	39

*Average data after testing ten heats

The Institute has developed a unit for welding up to 1220 mm diameter piles with up to 40 mm wall thickness, which was ordered by the oil and gas industry of Ukraine. The unit is designed as an outside machine, see Fig. 1, using the main modules which are already applied in the machines for welding smaller pipe diameters. The machine is installed on a column opening, where the pile is fed. It is fastened to the end of the pile being lowered with one clamp, the second clamp holding the pipes or section of two or three pipes being joined. The total efficiency in this case will be determined by the duration of support operations, since the welding time is comparatively short, and is not more than 600 s. By manufacturers' calculations, the implementation of such a technology will enable to increase by 8 times the productivity of the operation of incremental construction of piles. An industrial sample of such a machine will be produced in the coming years.

FLASH-BUTT WELDING OF PIPES UNDER WATER

The PWI has been carrying out developments in this field for the last 3 years. It is known that various kinds of arc welding performed in special high-pressure chambers are used to weld the critical joints of pipes. We believe that the application of resistance welding for the same purposes would offer a number of advantages compared to the currently applied technologies.

The main idea of using resistance flash-butt welding for joining pipes under water is not to place the entire welding machine into the chamber, but to create a local chamber around the butt to be welded. It is achieved by first mounting inflatable balls inside the pipes at a short distance for the place of welding, see Fig. 3, and by isolating the outer part from water by means of a detachable chamber, installed in the space between the resistance flash-butt welding machine clamps. Since the chamber casings are mechanically coupled with the clamps, the pipe clamping results in a simultaneous restriction of the water access to a certain area around the outstanding portions of the pipes to be welded. When air is fed to this area, the water is pressed out of it, and the air atmosphere remains from both sides in the welding zone. Flash-butt welding is performed in the same manner as in air.

Welding of up to 325 mm diameter pipes was performed in laboratory in a specially fitted machine. The outside machine was taken as a basis, it being used for welding on-land pipelines, see Fig. 4. A chamber was build into it, and the main electrical components, in particular, welding transformers, and hydraulic drive, were made in the form permitting their application under water. All the control systems are beyond the mechanical part of the machine and its operation is remotely controlled.

The welding technology was based on the same conditions which are used in resistance welding of on-land pipelines. Since in underwater welding the gas atmosphere pressure corresponding to the immersion depth should be maintained in the chamber, the influence of the gas pressure and composition in the chamber on the stability of the flashing process and welded joint quality was studied. The pressure varied from 0.1 to 3.5 MPa, corresponding to the immersion depths of 10 to 350 m. Welding was performed on 219 and 325 mm diameter pipes with up to 20 mm wall thickness, made of steels corresponding to X52 and X65 grades. Welded joints were tested in keeping with API requirements. Impact toughness tests of Charpy specimens at -10 °C temperature were also performed. The main parameters of welding are given in Table 3, and the testing results are shown in Table 4. The welding time for the mentioned pipes is from 160 to 180 s, the consumed power being about 250 kW. The welded joint strength properties are on the level of the appropriate properties of the parent metal, the impact toughness being lower in the as-welded condition. The subsequent heat-treatment which is done in the welding machine clamps enables a significant improvement of the joint ductility.

Table 3 Main data of underwater welding of pipes of 219 mm diameter, 18 mm wall thickness of X52, X60 steel grade

Air pressure in chamber, MPa	Welding time, s	Welding power, kW	Upset force, MN	Flashing displacement, mm	Upset displacement, mm
0,1	150	180	0.55	20	7
3.5	160	160	0.55	20	6

Table 4 Results of mechanical testing* of underwater welded pipes of 219 mm diameter, 18 mm wall thickness

Steel grade	Yield strength, MPa		Tensile strength, MPa		Impact energy J, -10 °C
	PM	WM	PM	WM	weld after heat treatment
Ст20	340	322	510	508	90
X60	431	418	592	585	88
X65	470	462	613	610	105

*Average data after testing ten heats

Air, argon, CO_2, and nitrogen were used as gas atmospheres. Changes of gas pressure in the chamber from 0.1 to 3.5 MPa did not produce an essential effect on the process stability and joint quality. No change of HAZ hardness when compared to open air welding processes was found. The gas composition also practically does not affect the joint quality. The mechanical properties of joints welded in argon or CO_2, are virtually the same, as in welding with air feeding into the chamber. It is accounted for by the fact that in flashing the intensive evaporation of metal results in the formation of natural shielding atmosphere of gas, differing by a low content of oxygen and high content of carbon monoxide (CO).

During resistance welding flash is formed in the place of welding from the outer and inner side of the pipe. In keeping with the specification, the inner flash has to be removed in most cases. In construction of on-land pipelines, which is most often performed by pipe increment method, special tools are used, which are introduced prior to welding into the pipe to be welded and remove the flash in a hot condition. In welding long pipe sections it is not possible to remove the flash from the closing butt with such tools. Therefore, we have developed several methods permitting to make joints in some cases with smaller flash sizes, and in other cases entirely without inner flash. One of the simplest methods is to make a special edge preparation, see Fig. 5 a. In this case the working cross-section of the pipelines in the welding zone is not reduced, and separate molten metal drops are removed with the standard cleaning tool during pipeline blowing through. With the second method end pieces are first welded to the pipe section ends, the end pieces being made of thicker pipes than the pipelines. The edges to be welded have special grooves, see Fig. 5 b, which form pockets during flashing, in which flash accumulates. These cavities are closed after upsetting and there is not metal thickening or overlapping on the inner surface.

The outer flash does not adversely affect the joint quality. The customers do not impose any restrictions on the outer weld shape or sizes, either. This section after welding is usually coated by a layer of mastic which covers the flash with a thick layer and has good adhesion with it.

During resistance welding of tens of thousands kilometers of on-land pipelines we have accumulated extensive experience of non-destructive testing of welded joints. The methods of ultrasonic and X-ray inspection are use. Besides that, the in-process inspection method has been extensively used for the last 15 years in practically all the welding systems. It is based on recording all the parameters, the change of which may affect the welding quality, and comparing them with the specified conditions. The considerable experimental data were the basis to establish the rejection criteria by the degree of deviation of each of the parameters from the specified one. The statistical material accumulated as a result of comparing the data of in-process and classical NDT methods demonstrates a good correlation of the control results. In several tens of thousands of reference butts checked by the in-process and NDT methods of control there was not a single case when the in-process control did not confirm the indications of the non-destructive one. Moreover, in a number of cases the in-process control led to rejection of butts which have been accepted by NDT. Their mechanical tests confirmed the correctness of rejection. Therefore, in our country the in-process control method is accepted by the codes as the main inspection method. Lately we have developed a computerized system of interpreting the in-process control results. It eliminates the need to employ qualified inspectors. The automatic control system prints out a document on the welding quality right after welding is over. In case of a butt rejection the cause which led to it is mentioned. Simultaneously, when the machine is switched into the welding mode, the system performs diagnostics of the condition of all of its components and allows to perform welding. Such a system has already been tried out in welding on-land pipelines and adapted for use in welding of pipes under water.

The technology of resistance butt welding of pipes under water and pilot samples of equipment have been tried out in the Black Sea water area in welding 219 mm diameter pipes with 10-20 mm wall thickness at the depths of up to 60 meters. The power to the welding machine was supplied from a floating crane power network of 300 kW power. Long pipe sections (up to 800 m) were welded, and repair of a section of pipeline was performed. Welding of pipe sections on land was also performed by resistance welding. Here, end pieces with a special edge bevelling were welded to their ends, and the surfaces of the pipes to be welded were cleaned in the places of their clamping by the current-conducting clamping shoes, prior to welding. A rough alignment of the pipes, with the diver participation, was performed under water. The subsequent operations of welding, unclamping and lifting of the welding machine were carried out without the diver, using remote control. In pipeline repair the diver participated in removing the soil around the damaged section, cutting out of this pipe section, cleaning of the pipe surface before welding, aligning of the new pipe-insert, which was first prepared on earth. Thus, the diver participated only in the performance of support operations. During experiments performed in the Black Sea several possible schemes of underwater resistance welding application were tried out.

The simplest schemes are the ones in which all the components to be welded are prepared on land, and only their alignment and welding are performed under water. Among such schemes are different versions of joining the long pipe sections transported over the sea, welding of the pipeline end of the support.

During work performance in the Black Sea, the joints made when welding the long pipe sections were tested. The joint quality is practically the same as in welding under the laboratory conditions. As a result of this work, initial data were prepared for compiling codes on resistance flash-butt welding application and development of a range of machines for this purpose. A machine has been designed for welding up to 530 mm diameter pipes with up to 20 mm wall thickness. The possibility of designing a machine for underwater welding of 930 -1220 mm diameter pipes is being studied now.

CONCLUSIONS

The technology and equipment has been developed for resistance butt welding of thick-walled large-diameter pipes, providing quality joints at low power levels (5 - 6 W/mm^2). Such a technology can be used for joining pipes during incremental building of piles in off-shore platform erection, it allowing to essentially improve the efficiency of welding works. A design of a machine for welding up to 1220 mm diameter piles has been developed.

Shown is the generic ability of applying the resistance flash-butt welding technology to join pipes under water in construction and repair of off-shore pipelines.

The application of this technology will make it possible to:

- avoid employing the divers-welders and considerably reduce the costs involved in the their life support when performing the welding operations;

- improve the safety of welding operation performance;

- considerably shorten the time of welding operation performance;

- provide the high and stable quality of welded joints, completely eliminate the influence of the welding operator's qualification and working conditions on it;

- eliminate the effect of the water depth on the welding quality;

- simplify the technology of welding quality assessment.

WET MECHANIZED UNDERWATER WELDING WITH SELF-SHIELDING FLUX-CORED WIRES

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The last years have seen a significant increase of the volume of underwater engineering works which are performed using welding processes providing satisfactory quality of joints at comparatively low cost. In this respect the wet welding process is preferred. It is versatile, highly flexible and comparatively inexpensive.

The method of wet mechanized underwater welding with self-shielding flux-cored wire has become the most widely accepted one in the CIS countries. It was created at the E.O. Paton Electric Welding Institute of the Academy of Sciences of Ukraine on the basis of extensive research and pilot design developments. Original self-shielding flux-cored wires, specialized semi-automatic welding machine and technology were developed to implement this process. It has several advantages over the process of wet underwater welding with stick electrodes, as it enables to essentially improve the quality of weld metal, process efficiency, reduces the effect of subjective factors on the welded joint quality. Magnetic arc blow is practically absent.

The A1660 semi-automatic machine was developed to perform wet mechanized welding at down to 60 m depth. The semi-automatic machine consists of two groups of components, namely immersible and non-immersible ones, which are connected by the welding cables and control circuit cable. The control cabinet is on the surface. It contains the system controlling the rotation speed of the electric motor for electrode wire feeding; system for semi-automatic machine protection from overloads and short-circuits in the motor circuit and instruments controlling welding parameters. The immersible unit is near the diver-welder. It holds the feed mechanism and a stock of electrode wire for semi-automatic machine continuous operation for 2.5 h at medium parameter level. The motor and feed mechanism provide a smooth adjustment of the flux-cored wire feed speed. Flux-cored wire is fed through the pressure mechanism rollers into the welding zone by a 2.5 m long flexible hose. The total weight of the immersible mechanism fitted with wire and the holder is 46 kg.

Power to the arc is fed from the welding converters or rectifiers with a flat external voltampere characteristics.

Flux-cored wires and technology were developed for mechanized underwater welding in fresh and sea water at down to 30 m depth. The required quality of welded joints is achieved in the low-carbon and some low-alloyed steels. The composition of the welded steels and weld metal is given in Table 1 and the mechanical properties of welded joints are shown in Table 2.

Analysis of the data in Tables 1 and 2 shows that even in case of not complex alloying the weld metal has sufficiently high level of strength and ductility. The noted difference in strength values is not an obstacle for an extensive use of the process for repair purposes, as the water works restored by welding have sufficient structural strength. This was proven by many years of experience of various structure service after repair by mechanized welding using flux-cored wires and technology developed at Paton Institute.

Table 1
Composition of the base metal and weld metal in underwater flux-cored wire welding

Steel grade	Analyzed zone	Elements, wt.%							
		C	Si	Mn	Ni	Cr	Cu	S	P
BCT3cΠ	BM	0.23	0.21	0.81	0.04	-	0.01	0.036	0.021
	WM	0.03	0.03	0.12	1.4	-	0.02	0.026	0.015
09Γ2	BM	0.13	0.4	1.4	0.03	0.05	0.12	0.014	0.026
	WM	0.03	0.03	0.15	1.4	0.03	0.08	0.019	0.025
10XCH	BM	0.08	0.65	0.53	0.57	0.59	0.36	0.032	0.024
	WM	0.02	0.02	0.09	1.65	0.08	0.12	0.021	0.017
A36 (USA)	BM	0.2	0.22	0.97	0.05	-	-	0.012	0.014
	WM	0.02	0.03	0.11	1.5	-	-	0.023	0.013

Table 2
Mechanical properties of welds in mechanized underwater flux-cored wire welding

Steel grade	Ultimate strength, G, MPa	Yield point G, MPa	Impact toughness, J/cm - 20°C	Bend angle, degr. R 40
BCT3cΠ	420...450	320...340	35...45	180
09Γ2	430...460	330...350	40...50	180
10CH	440...470	340...360	40...60	180
A36	420...460	320...350	40...50	180

Note: All the welded joints were tested in accordance with the Requirements of the American Standard ANSI/AWS D3. 6-89 for underwater welding using flux-cored wires and technology developed at Paton Institute.

Of considerable interest is the proposed technology assessment in accordance with ANSI/AWS D. 6-89 which was performed in the underwater technology laboratory of the Electric Welding Institute. Square-edge samples of 12.7 mm thick A36 steel shipped from the USA were welded and tested. Test data shows that the mechanical properties of welded joints correspond to class A of AWS D3. 6-89 specification.

Mechanized welding can be used to make butt joints in the downhand, vertical and horizontal positions. In overhead welding overlay joints are preferred.

Preparation of workpieces for welding and slag crust removal from the welds is performed with abrasive wheels and multi-striker tool. Welding can be performed both in fresh and sea water, with not less than 0.2 m visibility and up to 0.4 m/h current speed.

Performance of welding during salvaging the "Mozdok" ship which sank near Odessa to the depth of 32 m can be cited as one of the many examples. Flux-cored wire was used to weld a steel patch of 9x12 m size to the damaged side of the ship. During the last three years this method was used to repair, without placing in a dry dock, 40 ships just in the Baltic steamship line alone.

Considerable experience has been accumulated in gas- and oil pipeline repair. More than 50 underwater passages across rivers have been repaired. The main defects are cracks in field joints, corrosion pits, dents. A number of pipelines repaired by welding at the bottom of the Dnieper, Volga, Ob', Enisei rivers at the depth of 14...25 m have been operating successfully at 6 MPa pressure.

FITNESS FOR SERVICE DESIGN APPLICATION FOR UNDERWATER WET WELDS

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ABSTRACT

Underwater wet welding has been limited in use due to known difficulties associated with exposing the welding arc to the water environment. However, many recent investigations into the underlying problems of wet welding has yielded much greater insight for the development of superior welding electrodes, procedures, equipment and techniques which mitigate many of the problems or reduce their impact on the serviceability of wet welds. These developments and investigations have more fully defined the chemical, metallurgical and mechanical properties of wet welds and have pointed the way for development of even better properties. In conjunction with the welding investigations, innovative design concepts have been developed and tested that circumvent some of the wet welding problems and can be used to assure satisfactory performance. Coupled together, the improved properties and design concepts can be utilized to produce wet welding repairs and modifications to underwater structures and pipeline systems that are fit-for-service.

INTRODUCTION

The construction of offshore structures and pipelines has produced the requirement for repair welding or modification operations underwater. Underwater wet welding practices have historically been limited to depths of less than a few hundred feet because of the failure of electrodes and weldments to consistently achieve suitable soundness and toughness. The incentive to make wet welds is the direct and considerable cost savings that are realized compared to underwater weldments made either in hyperbaric or single atmosphere chambers. Most of the world's wet welding has been done in the USA and primarily in the Gulf of Mexico. Very few of the underwater welds made elsewhere are done by wet welding. However, the need for more reliable wet welds at greater depths is universal.

The wet shielded manual metal arc welding (SMAW) process has been favored due to the simple application, readily available equipment, and the speed with which it can be utilized. There are, however, many drawbacks in wet welding. The welds are quenched very rapidly often resulting in increased weld metal hardness and heat affected zone (HAZ) hardness. The evolved gases and the hydrogen and oxygen created by local disassociation of the surrounding water can be trapped within the weld metal as porosity. The hydrogen generated by the arc can cause hydrogen assisted cracking of the hardened HAZ and weld metal. Arc stability is affected by the water and can become progressively worse at increasing water depths. This can lead to slag entrapment and fusion difficulties that represent a determent to the weld quality. Additionally, chemical changes occur in the deposited weld metal and those effects are more pronounced with increasing depth and can lead to reduced mechanical properties of the weld metal.

Because of these difficulties, potential users of underwater welding techniques such as oil and gas companies and platform operators have not fully exploited the advantages of wet welding. Gas and oil pipelines are regulated by the API Standard 1104 "Standard for Welding Pipelines and Related Facilities". That document specifies the acceptance/rejection criteria for surface welds but does not address underwater wet welding. The American Welding Society Standard D-3.6 defines four types of underwater weldments as follows:

Type A: Welds intended for structural applications. These welds must have comparable properties to normal surface welds.

Type B: Welds intended for limited structural applications. These welds would be suitable to meet customer requirements for a specific application and normally include such jobs as temporary and/or permanent repairs or modifications.

Type C: These welds are intended to be crack-free welds where structural quality is not critical.

Type O: Welds that are intended to have quality equivalent to surface welds. These welds will meet customer specifications or codes for the structure concerned.

The majority of the present codes or standards do not consider fitness-for-service criteria when addressing wet weldments, particularly when the task at hand is a repair weld. It is sound engineering practice to utilize any given technique that produces a service satisfactory repair. For instance, API-1104 specifies a limit on weld porosity. Those limits were established based upon what might be reasonably achieved by a skilled welder using a qualified procedure, i.e., a workmanship standard. However, those standards may not be applicable to a given repair task. If small, evenly dispersed porosity does not impact the serviceability of the weldment, then there is no logical reason to exclude those welds from service. Therefore, application of a suitable wet welding repair is viable, even though increased levels of porosity and hardness and some decrease in ductility and toughness is experienced. Recent advances in filler metals, power supplies, and improved techniques have allowed wet welding in many structural applications. Wet SMAW welding procedures have been qualified in accordance with AWS D-3.6 Type B requirements and then successfully applied to repair and modification operations on offshore structures.

Further, innovative design concepts for specific repair operations can circumvent many of the problems associated with the reduced mechanical properties and add assurances that the wet weldment will perform satisfactorily as a permanent repair.

This paper presents a new concept for improving how wet welds are used for the repair or construction of underwater structures. A flexible intermediate connection pad is prefabricated on land and welded to the structural members in wet condition. This pad cushions the stresses on the joints. The inherently inferior impact properties of the wet weldments can be coped with by proper design of the connection pad. The wet welded joint can therefore fit its designed purpose.

Both theoretical analysis and experimental tests were conducted to demonstrate the design solution using the connection pad. A statistical data base on wet weld properties was developed to define the performance level of wet welds. The flexible connection was evaluated by impact testing for fitness for service. The results show that the performance of the connection can be improved through proper design irrespective of the low toughness of wet weldments. In addition, the fatigue strength of different wet welded joints is discussed.

Recently, there has been significant research and development in the field of wet welding. The investigators have identified a number of factors that control the applicability and suitability of wet welding. Broadly grouped, these factors are follows:

Metallurgical Considerations

- Cooling rate
- Chemical and microstructural features of wet welds
- Hardenability of weldments

Hydrogen Damage and Cracking Susceptibility
Porosity
Mechanical Properties
Electrode Selection
Wet Welding Design

METALLURGICAL CONSIDERATIONS

The metallurgy of welding is basic to the suitability of the resultant weldment. Thus, any changes in the microstructural features of a weld that are due to the water environment must be accounted for and understood.

Cooling Rate

The rate at which a weld cools affects the resultant microstructure of the weld metal and heat affected zone (HAZ) and the resultant hardness and crack susceptibility. Heat dissipation can be expressed in two ways. Cooling rate is expressed as degrees per second (C°/sec) at a given temperature or temperature range. Cooling time between two temperatures (such as the number of seconds to cool from 800°C to 500° C where the majority of metallurgical reactions take place) is expressed as T_{8-5} or S_{8-5} in seconds.

Researchers at Massachusetts Institute of Technology have conducted exhaustive studies[1,2,3] of the mechanisms involved in cooling of underwater weldments including the gas bubble dynamics associated with the welding arc. Using high speed photography of wet welds, it was concluded[3] that heat dissipation from the molten metal pool and local plate surface are primarily by heat conduction from the plate surfaces into the surrounding (moving) water. Water currents are generated by the rising bubble column in the arc area. Hasui and Suga[4] came to the same conclusion.

Plate thickness, welding position, and heat input also play an important role on the cooling rate. Cooling times $T_{(8-5)}$ can vary from one to four seconds for heat inputs that are typical for shielded metal arc welding (SMAW). Water temperature or depth has minimal effect on cooling rates or cooling times.

Chemical and Microstructural Features of Wet Welds

There have been a large number of investigations conducted on the metallurgy and resultant microstructural features of ferritic weldments published in the literature. However, there is significantly less literature that discusses the chemical and microstructural features of underwater wet weldments.

The predominately columnar microstructure of a single ferritic welding bead can contain a number of different transformation structures or microstructural constituents. The volume fraction and hardness of each of the constituents in a given weld bead is dependent on a number of factors, including; cooling rate from solidification, as deposited weld chemistry, prior austenitic grain size and the number, size, distribution and types of microscopic non-metallic inclusions.

The fact that wet welds cool much more rapidly than air welds further complicates the analysis of types and impact of the various micro constituents. However, there have been investigations[5, 6, 7, 8] that indicate that the desirable microconstituent is acicular ferrite (AF) as this constituent increases the notch toughness of the resultant weld bead.

Olson and Ibarra[9, 10] propose that the optimum inclusion content (oxides) should be controlled to produce an acicular ferrite "window" in the CCT diagram that will intersect a given cooling rate by altering the chemistry of the weld metal. It is widely known that wet welding increases the oxygen content (oxide formation) and that these oxides include those formed from manganese and silicon. The availability of oxygen in the arc atmosphere is from decomposition of the welding flux and from the ionization of the surrounding water [H] [O]. Thus, the deeper the wet weld, the greater the availability of oxygen and consequently the greater the loss of Mn and Si due to oxidation and the higher the volume density of oxides. These decreases in Mn and Si could significantly affect the microstructure, hardenability, and strength of the resultant weldment. A. Sanchez-Osio, et al[11] studied the effects of titanium and boron on the resultant microstructure of wet welds and concluded that the amount of acicular ferrite is controlled by the inclusion size and size distribution which can be modified with titanium and boron additions.

The microstructural features of a columnar weld bead are drastically altered by subsequent welding passes. These passes reheat the underlying weld passes to a temperature sufficient to cause the allotropic transformation to occur in a good portion of the underlying weld metal. This multi-pass recrystalization causes several zones of change. The last pass is columnar with the potential for all of the transformation products possible for a given alloy. Immediately below is a small area that has been reheated above the lower critical at a temperature and time sufficient to cause recrystalization and grain growth. The largest zone has been recrystalized but not at a temperature (or time) sufficient to cause grain growth and is normally characterized by extremely fine grain ferrite-perlite. The final zone has been reheated to a temperature insufficient to cause recrystalization and remains columnar in nature but may have been significantly altered by precipitation reactions.

The elimination of a significant portion of the columnar structure and replacement with reheat treated structure increases the mechanical properties of the total weld deposit. Hoffmeister and Kuster[12] show a significant increase in the Charpy Vee Notch (CVN) toughness of multiple run weldments. Hoffmeister[13] also indicates a decrease in CVN energy with increasing austenitic grain size and concludes that multilayer welding improves toughness.

The heat affected zone (HAZ) produced in the base material is affected by the effective heat input, the cooling rate and the degree of alloying, i.e.; the carbon equivalent (CE) of the base metal. For underwater wet welds, the cooling rate is always very fast and thus, any hardenable base metal will produce a predominately martensitic HAZ near the fusion line. This hardened zone is susceptible to hydrogen assisted cracking and restraint cracking and displays poor ductility.

Based upon the literature and results of testing, the following general comments appear appropriate:

1) The microstructural constituents (microphases) of underwater welding are controlled by heat input, prior austenitic grain size, cooling rate and alloy content.

2) The alloying elements Mn and Si are significantly reduced during wet welding by oxidization reactions. Increasing depth further decreases Mn and Si but the majority of change is within the first 50-100 FSW.

3) There is conflicting evidence on the effect of depth on Carbon. Several investigators report increasing Carbon at depth and other data shows only minor changes or a reduction in weld metal carbon. It is surmised that the flux covering and chemical make-up of the electrode plays a major role in these reactions and may well be different for various electrodes. Also, the degree of dilution with the base metal would play a part in Carbon pickup.

4) Strong deoxidizers such as Ti, B, Zr and Al can alter the burn-off of Mn and Si but cannot eliminate the effect.

5) Additions of other alloying elements such as Mo, Ni, Cr, Va can alter the CCT curves for welding and promote desirable microstructures provided that the hardenability is not increased to a degree that would cause weld metal cracking.

6) Acicular ferrite is a desirable microstructure as it increases notch toughness. The

small nonmetallic inclusions formed by oxidization reactions can (at an appropriate volume density and size) promote the formation of acicular ferrite and increase the notch toughness of the columnar weld metal. Controlled additions of Ti and B can modify the inclusion content of wet welds.

7) The bulk of wet SMAW welding is performed with relatively small diameter electrodes using multiple weld beads. This technique causes reheat treatment of both the underlying weld metal and the HAZ producing the overall weld zones discussed previously. The recrystalized weld microstructures in Zones II and III make up 50% or more of the deposited weld metal and are fine grained (equiaxed) microstructures that should perform well in notch toughness and strength. Welding technique, arc power, travel speed, electrode burn-off rates and depth of penetration will alter cooling rate and the volume fraction of each microstructural zone.

Hardenability of Weldments

The hardenability of a given base metal or weldment is controlled by its alloy content. There have been several formulas developed to calculate hardenability, normally expressed as a Carbon equivalent (CE). These formulas assign a numerical factor for each element and its effect on hardenability. The CE (%) formula adopted by the International Institute of Welding (IIW) in 1967 was [CE = C + Mn ÷ 6 + (CR + Mo + V) ÷ 5 + (Cu + Ni) ÷ 15]. This same formula has also been adopted by the American Welding Society's "Specification for Underwater Welding", D.3.6 as an essential variable.

The literature is rich in quoted hardnesses data for weld metal and especially the HAZ. However, these data cover a very wide range of welding parameters, electrodes, and alloys.

Therefore, it is difficult to define the role that hardenability plays in the suitability of underwater welds.

Dexter, et al[14] performed a statistical analysis of wet SMAW weld properties that had been published in the literature. The analysis included the independent variables CE, wet or dry, thickness, depth, welding position and polarity. As expected, a very strong correlation was found between the independent variable CE and the dependent variable hardness (HAZ). Based upon the data available, the prediction equation for peak HAZ hardness was: HVN = 282 + 566 (CE). However, subsequent wet welds made in that program were tested for peak hardness and it was found that the formula significantly overestimated the hardness. The program included wet ferritic SMAW welds from 33 FSW to 198 FSW and air welds for baseline information. This work concluded that HAZ/weld metal hardness could not be correlated with tensile strength, notch toughness or bend ductility in weldments that did not display cracking.

The peak HAZ hardness at the toe of an under water wet weld is an extremely small zone. The band of martensite formed is reported[2] to be less than 0.5 mm wide and could be no longer than the base metal intersecting periphery of the weld bead. All underlying weld HAZ will have been tempered by subsequent welding passes to some extent. Thus, peak hardnesses may be a poor gage for overall weld performance. The same argument can be made for weld metal hardness, i.e.,; the crown layer and in particular, the last pass, are the only untempered microstructures in a multipass weld made with moderate to low heat inputs. These tempered zones are significantly lower in hardness and thus more resistant to delayed cracking.

Temper bead welding has been shown (Ibarra, et al[15]) to significantly reduce the peak HAZ hardness. Szelagowski, et al[16] investigated the post weld heat treatment (PWHT) of wet welds using a separate heat source to temper the hardened HAZ. Significant reduction in HAZ hardness as well as diffusible hydrogen were attained. Thus, it is possible to mitigate the problem of excessive hardness although the techniques used would increase the required welding time.

HYDROGEN DAMAGE AND CRACKING SUSCEPTIBILITY

The types of cracking experienced in ferritic wet welding are generally hydrogen assisted cracks (HAC), also known as cold cracking, HAZ cracking, underbead cracking, etc. It is generally recognized that HAC requires three separate conditions, i.e.; a susceptible microcstructure, a source of hydrogen and stress. The elimination (or sufficient reduction) of any one of the variables will preclude HAC.

Hydrogen

The availability of hydrogen in wet welding is extremely high. This abundance is due to the disassociation of the water in the immediate vicinity of the welding arc into [H] and [O]. Also, any moisture tapped within the electrode coating or any hydrogen producing compounds will supply hydrogen to the arc plasma. The molten weld pool is thus subjected to large quantities of hydrogen and (in the molten state) can dissolve a significant amount. Upon cooling, the lower solubility of the molten pool will reject a portion of the hydrogen which combines to H_2 and forms porosity when there is insufficient time to escape before solidification. The remainder is trapped within the crystal structure as atomic hydrogen [H] and is free to diffuse within the solidified metal.

Numerous investigators have studied the amount of diffusible hydrogen (H_D) produced by wet welding. The levels of H_D reported are significantly different depending upon the welding process used, the type of electrode and its flux covering, the heat input and arc voltage and the cooling rate.

Cracking Susceptibility

There have been a significant number of wet weld investigations on the cracking susceptibility of various weld metals and base metals. The data reported shows a large variance in results and depends upon the welding heat input, electrode selection, diffusible hydrogen, base metal hardenability, weld metal composition and the restraint of the weld. In general, it is reported that HAZ cracking (HAC) is the most common form of wet weld cracking and that this cracking correlates to the carbon equivalent of the base metal, i.e., increasing CE produces increasing HAZ cracking. Relatively large data bases[14, 17, 18] have been analyzed and the stated "rule of thumb" is that CE of 0.40% can be welded with ferritic electrodes without undue danger of HAC. The use of the temper bead or PWHT techniques has yielded satisfactory welds on even higher CE material. The use of austenitic filler metals further expands the CE envelope.

POROSITY

The increase in the quantity and size of weld pores with increasing depth has been documented by every investigator of wet welding. The formation of these pores is controlled by the solubility of the various gases (principally hydrogen) in the molten metal. Subsequent rapid cooling reduces the solubility and rejects the dissolved gases as molecules which form bubbles in the molten metal. Wet welding solidification is so rapid as to prevent these bubbles from rising to the surface of the molten metal and escaping, thus being trapped within the solidified metal. These pores reduce the net section of the weld causing a reduction in strength, ductility and toughness. As mentioned previously, there are things that can be done to mitigate the formation of pores but they have as yet been eliminated. Suga and Hasui[19] conducted controlled experiments at water depth of 0 to 6 atmospheres using three different ferritic electrodes, i.e., TiO_2 type, ilmenite type (TiO_2 + FeO) and Fe - F_e0 type. The resultant porosity levels were measured and showed a steady increase in % porosity with increasing depth. The porosity did not form until 0.5 atmospheres after which it increased up to 9% at 6 atmospheres.

Suga and Hasui further investigated the formation at the pores and concluded that there are two different pore morphologies formed at low and high pressure. Below 99 FSW the pores form near the fusion line and grow along the solidification lines. At higher pressures, i.e. greater than 100 FSW to 200 FSW, the pores have a tendency to occur in large numbers in the upper part of the weld bead. The lower pressure pores are more spherical in shape whereas the high pressure pores are more elongated, i.e., piping porosity. They concluded that porosity formed below 3 atmospheres (called Type A pores) were formed due to concentrated hydrogen at the solidification front. Deeper, Type B pores are formed within the molten metal as evidenced by solidification lines around the periphery of the pore. These pores are trapped by the progressing solidification front.

The above conclusions tend to agree with other information. Dally[17] reported excessive piping porosity in ferritic welds made at 330 FSW. Wood et al[20] reported on a temporary repair weld made at 560 FSW in which the porosity amounted to 32% of the welds cross sectional area. Another investigation disclosed piping porosity was the prevalent pore type in welds made at 300 FSW. The percent porosity averaged 3.8% at 34 FSW, 4.5% at 100 FSW, 5.0% at 200 FSW and 10.6% at 300 FSW.

Grubbs[21] reported only small diameter, evenly dispersed porosity at 325 FSW. Although not quantified, Grubbs also reported on 45 other weld ferritic welds at depths up to 150 FSW. Only six of those welds were reported to contain excessive porosity. Szelagowski et al[22] reported that porosity percentages varied significantly with the type of ferritic electrode used. All were rutile type electrodes from different suppliers. One electrode displayed 0.5% porosity at 180 FSW and 3.8% at 330 FSW. Another displayed 1.0% at 180 FSW and 2.5% at 330 FSW. A third displayed 0.6% at 180 FSW and only 1.0% at 330 FSW. Although the porosity was not separated in to spherical versus piping, the macrographs show an increase in piping porosity for the deeper welds. The Dexter[14] work on welds made using a proprietary E-6013 electrode displayed basically spherical porosity for welds at 33 and 115 FSW with a significant increase in piping porosity at 198 FSW. The percentages were 1.0% for 33 FSW, 3.7% for 115 FSW and 4.7% for 198 FSW.

Sanchez-Osio, et al[11] tested a range of calcium carbonate additions to an E-6013 welding electrode. The minimum porosity was associated with a 12.5 wt.pct C_aCO_3. Higher additions sacrificed in arc stability, and caused higher voltages resulting in an increase in porosity.

All of the investigators reported an increase in porosity with increasing depth. However, there is a wide range of reported percentages at various depths. This scatter in data is likely linked to the type of electrode used, the skill of the welder, arc voltage, and water-proofing compounds.

MECHANICAL PROPERTIES

Discussion

The mechanical properties of wet weldments are known to be inferior to those of dry welds. AWS D3.6 defines the mechanical properties tests that must be performed for each of the weld types, i.e., A, B, C and O. Not many years ago, wet welding was believed to be suitable only for Type C classification. However, the industry has improved and refined wet welding to the point that Type B welds are regularly developed and qualified for use under the requirements of D3.6, and many of the welds pass Type A requirements for weld soundness, strength and notch toughness. This document specifies the essential variables necessary to qualify a welding procedure and specifies the minimum quality, soundness, and mechanical properties as measured by visual test (VT) radiographic (RT), tensile test (UTS, YTS), bend test (BT), charpy notch toughness (CVN) and metallographic testing.

Numerous investigators have investigated the mechanical properties of wet weldments. Most determine that the wet welds display reduced tensile strength, elongation (E_L), reduction in area (RA), bend ductility and charpy notch toughness (CVN) when compared to air welds using the same electrode. Weld flaws such as trapped slag, inadequate penetration (IP), incomplete fusion (IF), cracking (both macro and micro), undercut (UC) and porosity may increase with increasing depth of welding. Proper electrode selection, procedure development, welder skill, training and attention to detail can control all of the above mentioned flaws except porosity. However, the chemical and metallurgical reactions that occur cannot be controlled by the welder. The loss of Mn and Si with the increase in Oxygen and reported increases or decreases in carbon can drastically alter the mechanical properties of the weld metal.

Experimental Results

Dexter[14] et al gathered most of the mechanical properties test data on wet SMAW welds published through 1984 and performed a statistical analysis of the data. In addition, that program entailed wet welding with ferritic electrodes and subsequent testing by hardness, VT, RT, UTS, BT, CVN and a fracture toughness test (FT) J_{IC}/K_{IC}. Welding depths were air, 33 FSW, 115

FSW and 198 FSW. Analysis of the data led to the following (summarized) conclusions:

1) The tensile strength of the welds exceeds the rated strength of the electrodes. The ductility (both bend and tensile EL) decrease with increasing depth, but meet the requirements of D-3.6. The shear strength exceeds 60% of the base metal and all weld metal tensile strength.

2) The fracture toughness of the weld is sufficient to allow flaw sizes greater than those limited by AWS 3.6. All FT tests failed in a ductile tearing mode. The CVN tests yielded upper shelf fracture at 28°F. The HAZ is as tough as weld metal for thick plates (1.0 in) and tougher than weld metal for thin (0.5 inch) plates. The weld metal toughness decreases significantly with depth, but displayed upper shelf at 28°F for all depths.

3) Porosity increases with increasing depth. No cracks were observed for full penetration or fillet welds at any depth for ferritic welds.

4) Hardness in the weld metal or HAZ could not be correlated to bend ductility, notch toughness or strength performance.

5) Fracture toughness tests (CTOD, J_{IC}, K_{IC}) were correlated to Charpy CVN.

The above work did not include changes in weld metal chemistry and its effect on the values obtained. Subsequent work disclosed a strong relationship between the welding depth and the combined (Mn + Si) elemental loss with the curve flattening at approximately 100 FSW. Also, the data indicated a linear, steep slope relationship between fracture toughness (K_{IC}/J_{IC}) and Charpy CVN values with increasing toughness with increasing Mn and Si. The CVN and FT values dropped with increasing water depth as did the all weld metal tensiles.

Dally, et al,[17] conducted another extensive evaluation which included wet welding at depths of 33, 165 and 330 FSW using ferritic electrodes and an A-36 steel with a CE of 0.384%. A summary of results indicated the following conclusions:

1) HAZ cracking (HAC) can be avoided by proper electrode selection and welding procedures in steels with a CE of less than 0.4%, even with H_D levels of 61 mℓ/100 gm.

2) In addition to CE, the yield strength, carbon and silicon content may also affect the cracking susceptibility.

3) The hardened HAZ with peak values up to HVN 453 at the top of the welds did not produce cracking or cause failure of bend tests in accordance with Type B requirements of D-3.6. The HAZ toughness tests normally out performed the base metal.

4) Weld metal porosity increased with depth. The UTS and EL decreased with

increasing depth but remained at 65.9 ksi at 330 FSW. The CVN tests disclosed upper shelf (100% shear) properties at service temperature although the upper shelf impact energy decreased with increasing depth. The drop weight nil ductility transition temperature was a low -50°F for a weld made at 33 FFW.

5) Fracture toughness testing showed a decrease in toughness with increasing depth but the resistance to crack propagation remained high with no brittle crack extensions (pop-in) during testing and all failed by ductile tearing.

6) Crack arrest tests showed that it was not possible to initiate or propagate a brittle crack in weld metal at temperatures above -20°F.

7) Fatigue and corrosion fatigue testing was performed on wet and dry ferritic welds including the hardened HAZ at the toe of the weld. The wet weld out performed the dry weld.

The results of these two programs is not inconsistent with other investigations. Gooch[(23)] reported UTS, YTS, EL and RA for a number of wet welds made with a number of ferritic electrodes with different flux coatings for shallow water welding. He reported average all weld metal tensile strengths of from 65.5 to 80.2 ksi with yield strengths from 56.8 to 80.2 ksi. The elongation was reduced to as low as 5%. There was a large scatter in the CVN results depending upon which electrode coating was used. Oxidizing iron oxide coatings produced the lowest values (10 ft lbs at 32°F) of the ferritic weld metals. The highest values were displayed by the rutile coated electrodes at 26 ft lbs. CTOD testing disclosed that the ferritic weld metal suffered. Some cleavage fracture was detected in the oxidizing iron oxide electrode but better values with ductile behavior was displayed by the rutile electrodes. Gooch also conducted fatigue tests and stress corrosion cracking (SCC) tests. The fatigue life was reduced somewhat but was not drastically lower than corresponding air welds. The SCC in a saline environment disclosed no evidence of cracking, even with a fully hardened HAZ. Gooch concluded that, given reasonable freedom from welding defects, the tensile strengths exceeded parent material yield and that the toughness (although reduced) remained quite high at temperatures of practical interests.

Grubbs[(18)] et al reported a large matrix of tensile tests associated with welding procedure testing on base materials with varying CE from 0.188 to 0.480%. The transverse UTS varied from 56 to 77 ksi. The E-6013 welding electrode displayed an average all weld metal UTS of 64.2 ksi and a YTS of 56.8 ksi with an E_L of 7.5% and an RA of 7.7%.

Subsequent work by Grubbs[(21)] was performed at 165 and 325 FSW. The 165 FSW all weld metal tensile test produced a UTS of 63.2 ksi an YTS of 60.5 ksi with an EL of 9.5%. The 325 FSW weld produced a UTS of 58.8 ksi, YTS of 56.3 ksi and EL of 6.5%. Both welds met the criteria for AWS D3.6.

Cochrane and Swetnam[(24)] welded ferritic electrodes in 10 feet of fresh water and performed the range of mechanical tests required by D3.6 and in addition performed CVN and CTOD tests. The welds met the D3.6 acceptance criteria and the toughness testing (CVN and FT) showed acceptable toughness down to -20°C.

Matlock[25] et al performed fatigue testing on dry, hyperbaric and wet weldments in air and in seawater and made by two different suppliers using E-6013 electrode with varying coatings. The welding depths are between 24 and 33 FSW. They reported that the porosity produced in wet welding altered the crack propagation rates in fatigue. At low values of stress intensity factor range (ΔK) the porosity effectively pinned the crack front and retarded crack growth, and the crack growth rates decreased with increasing pore density. For high values of ΔK, the porosity decreased the load bearing area and increased the local stress at the crack tip producing higher growth rates. Subsequent fatigue tests in seawater disclosed that at low ΔK the seawater propagation rates were less than corresponding tests made in air and that high ΔK produced faster propagation rates. The affect of cycle rate was that low cycle rates produced significantly faster propagation rates than high cycle rates. At high cycle rates the affects of porosity observed for air tests was not observed in sea water. At low ΔK the effect of sea water was to retard crack growth for both low and high pore density.

Summary

Reviewing the available data on properly made wet welds leads to the following conclusions:

1) Porosity always increases with increasing welding depth. This porosity reduces the net section area and therefore reduces weld metal strength. There is strong evidence that porosity can be reduced using altered flux coatings.

2) The loss of alloying elements, particularly Mn and Si reduce the tensile strength of the weld metal at greater welding depths. These losses can be mitigated by controlled additions of strong deoxidizers or increases in the base formulation of tle electrode.

3) The bend and tensile ductility of wet weld metal is significantly reduced and this effect is more pronounced at increasing water depths. This is likely due to the loss of strengthening elements, hydrogen induced microcracking and increase defect level. However, the bend tests normally meetD.36 criteria and often exceed those requirements.

4) The notch toughness as measured by CVN and FT testing decreases with increasing depth.. The upper shelf impact energy is lowered significantly but the fracture appearance remains high at temperatures appropriate for the intended service. Fracture toughness and crack arrest properties display ductile behavior at practical temperatures. The nil ductility transition temperature as measured by the drop weight test can be well below service temperatures.

5) The peak hardness of HAZ is only marginally affected with increasing depth and remains high, i.e., normally greater than KHN 400. The bulk of the tempered HAZ in multiple pass welds is normally much softer, often reduced to KHN 300 or below. The bend and tensile performance of this narrow zone appears to be satisfactory. The notch toughness and fracture toughness of this zone is

considered satisfactory. Temper bead welding or PWHT procedures can lower the peak hardness significantly.

6) The peak hardness of the weld metal is always in the capping layer and is usually less than KHN 300. Underlying tempered weld metal is much softer.

7) The fatigue and corrosion fatigue resistance of wet welds are comparable to dry welds and at low stress intensity ranges the porosity can retard crack propagation rates, both in air and salt water environments.

8) The stress corrosion cracking behavior of wet welds does not appear to be different than corresponding air welds, even though the HAZ is typically harder.

ELECTRODE SELECTION

The importance of the electrode used for wet welding an not be overstressed. The evolution of the wet welding industry has involved the development of many proprietary electrodes, some of which are commercially available and some of which are restricted to the use by the developer. Industry has also used standard, commercially available electrodes that have not been modified for underwater use except for a water proofing coating. For ferritic wet welding, the vast majority of both proprietary and commercial electrodes use are of the AWS A5.1 E-60XX or E-70XX type. The two most dominate usages are E-6013 and E-7014. However, there are significant differences from supplier to supplier of such electrodes. The core wire for the E-60XX and E-70XX electrodes is normally very nearly the same chemical composition, i.e., relatively low carbon steel with controlled additions of Mn and Si and normally low values of S and P. Minor additions of other elements such as Ni, Cr, Mo, Cu or V may be made to obtain the strength requirements of the specifications. Each electrode manufacture has developed his own flux covering.

These flux coverings may contain a large number of minerals and compounds that are intended to produce the slag, deoxidize the molten pool, alter the slag viscosity, stabilize the arc, decompose in the arc to form shielding gases, provide improved extrusion capabilities, provide binding for covering strength, and add minor alloying elements. The individual manufacture formulates their own covering and carefully guard their specific formula. This is particularly true for commercially available wet welding electrodes, and thus, there are not specific formulas published in the open literature.

There have been a significant number of wet welding investigations that have been directed at evaluation of the standard electrode types for wet welding. Stalker[26] conducted extensive testing of 17 different ferritic electrodes, including celluosic, rutile, oxidizing iron oxide (both acid and basic) with and without iron power additions. Based upon bead on plate welds in shallow water he reported that the basic coated electrodes were inferior to the others as far as operability was concerned. Rutile ($Ti0_2$ - E-6013), acid iron oxide (Fe0 - E-6020) and iron powder (E-7024) yielded the best operability. Straight polarity (SP) was superior to reverse polarity (RP). The E-6020 electrode produced the lowest H_D of all ferritic welds but residual hydrogen was the highest. He attributes the better performance of H_D to the high oxide inclusion content of the E-6020 deposit along with the very lean as deposited chemistry.

West[27] performed an extensive evaluation of commercially available wet welding electrodes, i.e., electrodes developed for wet welding. Six ferritic electrodes identified as either E-7014 (type) or E-6013 (type) were welded at 33 FSW in a cruciform screening test. The results rejected all of the E-6013 types and two of the E-7014 types leaving only two E-7014 types for further testing. The two electrodes were used for all position butt welding trials. The results indicated the following conclusions:

1) Both welds met AWS D3.6 criteria for radiography and bend testing at a restricted (4T) bend radius.

2) Both met the Naveships requirements for Class 2 on visual examination, and Class 1 for magnetic particle and liquid penetrant testing.

3) The tensile properties were equal to, or better than the base metal.

4) Both displayed reduced ductility (EL) and notch toughness (CVN).

Gooch[23] conducted a two part evaluation program that involved 12 separate ferritic electrodes in shallow water and a limited number at 100 feet of water. Heat input, plate thickness and CE were varied and the resultant H_D, mechanical properties and cooling rates were measured. The lowest H_D level was displayed by the oxidizing iron oxide coating which produced a high inclusion density which is consistent with Stalkers[26] work. He reported that basic coated electrodes produced the poorest operability and rutile (6013/7014) or acid/rutile produced the best. All others fell somewhere in between. The rutile coatings produced fewer defects (other than HAC). The ferritic electrode welds were all susceptible to HAC except oxidizing iron oxide which displayed poor operability, arc stability, tensile and notch toughness.

There have been many other programs that produced information on various commercial and proprietary electrodes. Many have been qualified in accordance with D3.6 or owner specifications. The above mentioned programs compared the results of one type of electrode to another. The following conclusions are made based on a review of all applicable data whether referenced or not:

1) Given the presently available range of ferritic electrodes the following comments can be made:

   a) Wet welds will always display hardening in the weld metal and HAZ when compared to dry welds.

   b) The operability and resultant bead profiles can be satisfactory.

   c) The defect level can be maintained at a suitably low level.

d) The porosity level may vary from electrode to electrode but can be maintained at a usable level.

e) Tensile strength can be generated that are sufficiently close to air welds as to allow their use for structural applications.

f) The ductility and notch toughness are presently much lower than corresponding air welds but can be high enough for a given application.

2) Either E-6013 or E-7014/7024 electrodes produce the best operability. This is not surprising as it is those electrodes that are most widely used in industry.

3) The various electrodes and their flux coating can produce significantly different usability, operability, arc stability, bead profiles, penetration, hydrogen pickup, porosity and other welding flaws, which impact tensile strength, ductility and notch toughness.

4) It is not clear why some electrodes out perform others. The scatter in the results produced by different investigators on the same electrode types would indicate that only minor changes in flux composition can alter the results. It may also indicate that only minor changes in the welding parameters may alter the results.

5) Minor alloy additions to the core wire or through the flux coating could be beneficial to the production of superior mechanical properties, particularly for replacing those elements lost during wet welding.

6) Gas producing (other than H_2) compounds can increase the arc stability by providing an easily ionizable path for the arc as well as displacing hydrogen and providing protection of the weld metal droplets and weld pool prior to solidification. Hydrogen getters could also reduce the amount of hydrogen available. Oxygen getters could reduce the loss of certain alloying elements.

7) Water proofing compounds can effect the wet welding characteristics of a given electrode. The most advantageous are those that accomplish their function without degrading the operability or interfering with the vision of the welder.

8) There is likely to be a different optimum electrode/flux combination for different welding depth ranges.

WET WELDING DESIGN

Background

This paper presents a new concept for improving the use of wet welds for underwater structure repair or even construction. Typically, structural members would be directly joined to each other. The new concept is a novel design that cushions the stresses on joints by welding a metal "pad" between the two structural members. A portion of the welding is done in air and the final product is underwater wet welded. The design of the joint does not allow the full impact energy imposed on the structure or the stresses the structure undergoes to be put upon that portion of the structure which is the weakest, the underwater weld joints.

With the new design, a flexible intermediate connection pad is welded together outside the water. After the critical pieces are connected, the assembly is submerged and attached to the underwater structure using wet welding.

In order to develop this design concept, the performance level of wet welds must be known. It was decided that the performance level of wet welds would be determined by static strength, Charpy impact strength, and microhardness during this study. A statistical data base that was developed from a literature review and experimental tests.

The next step in the study was to conduct connection design iterations using the finite element method. The stress distribution in the wet welds and the strain energy absorbed in the flexible connection pad were determined for the minimum weld size and the optimum flexible connection pad dimensions for different loading conditions. The weld performance data was used as the design criteria in the analysis.

Finally, tests were carried out in the laboratories to demonstrate the effectiveness of this design approach. These tests indicated agreement in trends between computer predictions of impact strength and the laboratory trials.

Mechanical Properties

For this study the identification of the mechanical properties of wet welds was collected from current literature and from the testing of welds made under simulated offshore conditions (*i.e.*, welds that were made in a diving tank). A database was developed for this study. This database is divided into two parts. The first part of the database was derived from the literature search and covers a full range of various underwater wet welding activities. The second part of the database consists of test results from actual mechanical tests of the wet welds performed for this study and from other research where the welding procedure exactly matched the procedure for this research (*i.e.*, shielded metal arc welding of ASTM A36 base metal with tensile, Charpy V-notch and hardness tests). The compilation of the database is shown in Zirker's M.S. thesis[28]. The current work involves microhardness traverses (Knoop) and fatigue tests carried out using different types of flux-coated electrodes (shielded metal arc welding of ASTM A588 base metal, cruciform joint) by Tsai, et al[29].

As a relative measure of the mechanical properties of wet welds with respect to their air-welded counterparts, quality indexes were used to perform the statistical data analysis. The statistical analysis of this database is shown in the form of a bar chart graph–Figure. 1.

Figure 2 shows the microhardness (DPH) distributions in the various metallurgical zones of both underwater "wet" welds and air-welded counterparts. The hardest zone on a ASTM A36 steel weldment made underwater is about 0.5 mm (0.02 in.) from the fusion line. The overall hardness of the underwater wet welds is much higher than its air-welded counterparts due to the rapid quench effect in the wet welds. Figure 3 shows the microhardness distribution (Knoop) of underwater wet welded joints made with different flux-coated electrodes[29]. The microhardnesses indicate the same trend as that shown in Figure 2. Figure 4 shows the fatigue strength of underwater wet welded joints and air-welded counterparts produced by Grubbs and Zanis[30].

Figure 5 shows the fatigue strength of the tested electrode[29]. Note that for all single pass joints, fracture occurred in weld metal; while for all multipass joints the fracture occurred at the weld toe.

To characterize the true performance level of joints with Type B welds as opposed to joints with Type A welds. A three-axis fitness-for-purpose index (FFPI) system was developed. This system is based on the test results to show the relationship of three mechanical properties: tensile strength, Charpy V-notch and hardness. Each axis corresponds to one of the properties. Each property axis was divided into six ranges along the axis – Figure 6. The algorithm tables were divided by inserting data points that fall into test range cells in the planes along the hardness axis.

Figure 6 also shows the six algorithm tables use to develop the FFPI system. The values of each of the 17 data points were placed in the appropriate cell within one of the tables. Each table corresponds to one of the ranges on the hardness axis in the FFPI system.

The points within the plane cells were plotted on the three-way FFPI axis. By way of comparison, a super imposed box shows the approximate quality range for a Type A weld.

Confidence factors were computed from the Type B data range along the hardness axis. However, 90% of the FFPI welds fell within the Type A range considering tensile strength and Charpy V-notch values. The hardness limitation of 325 Vickers (DPH) is the most difficult of the mechanical properties to achieve.

Welded Connection Design

Given that there are some doubts as to the true performance level of wet welds, a good wet welded connection design places the wet weld of the joint in a noncritical, but structurally sound location. Obviously, defect-free wet welding would be ideal, but is not feasible. The use of full-penetration V-groove joints is not conducive to defect-free underwater welding, especially for pipe or tubing. Groove welds are inherently difficult, but in the wet weld environment, the overhead position of the joint is very difficult. For these reasons, the choice of fillet wet welds is more desirable since they are usually more defect-free and easier to install under water.

A wet welded joint must support the applied design load. Initial design criteria must allow determination of connections strong enough to withstand these applied loads, with appropriate safety factors. The other considerations are such problems as fatigue and brittle fracture.

The fatigue design is primarily a geometric problem. The AWS D1.1 code defines levels of fatigue performance using the stress range vs. life cycle (S-N) curves for different geometric categories of the welded joints. In addition the weld profile, especially at the weld toe, causes stress concentration and initiates premature cracking. The wet welded joint must be designed so that acting cyclic stress at the weld toe be less than the allowable stress.

When the welded structure is subjected to impact loading, or dynamic loading at high rate, the kinetic energy due to impact must be transformed into either motion (*i.e.,* kinetic energy) or deformation (*i.e.,* strain energy) of the structural members, or a combination of both effects. The resulting motion of the structural members dissipates the energy into the surrounding environment. The remaining energy stresses the structural members, including the connections joining the structural members.

The welded connections, as an integral part of the structure, play a significant role in determining the proportion of these two types of energy transformations in the structure. Cracking will occur if the strain energy density in the weldment exceeds the resilience of the weld metal or heat-affected zone. Charpy V-notch toughness indicates the impact resistance of the bulk material with the effect of notch stress concentration. Therefore, Charpy V-notch toughness of the weldment can be used to characterize the weld strength to resist impact loads.

As indicated by the weld property database, underwater wet welds are statistically strong enough to carry any structural loads. However, these welds can display low Charpy toughness and high hardness and have reduced capacity of absorbing the impact energy. Brittle fracture might occur if these welds are subject to a direct impact at temperatures below the nil ductility transition temperature (NDTT).

Combining energy loss with energy absorption devices like springs or rubber shock absorbers, the total impact energy absorbed by the connecting underwater welds can be minimized by using a flexible, intermediate connection pad. By design, the energy dissipates into the connection pad before reaching the underwater welds, and the impact energy at the underwater welds is minimized. The strain energy density in these welds is, therefore, kept below its toughness (resilience) limit. Brittle fracture of underwater weldments due to impact loading can be eliminated. The underwater wet welds are able to perform the intended structural functions.

Flexible Pad for Tubular Structural Connections

The design philosophy for a flexible connection pad is that an air weld can be substituted for a wet weld at critical positions where stress concentrations and high stress fields exist. The wet welds are placed at low stress locations and the flexibility of the pad improves the energy absorption of the joint. Also the weld profile and toe contour of the air welds is more consistent, controllable and capable of withstanding higher stress concentration factors than the wet welds. This design concept can be expanded even farther for conditions requiring increased flexibility by using a multilayer pad design.

Typical tubular connections are the T, K, Y and X. Often these connections in offshore structures are braced in multiple planes, and the use or analysis of such structures would be beyond the scope of this study. The T connection shown in Figure 7 could be modified to include other connections, but for simplicity, the T connection and single layer pad design were used for this study.

The finite element method (FEM) was used to analyze the stress distributions and energy absorption of the tubular connection. Optimum pad dimensions were determined for different variations of loading conditions. The geometric variables studied are shown in Figure 8.

The design variables related to the pad geometry are pad length, (L1); pad thickness, (T1); and height of the arc, (H). These variables were normalized with respect to a constant pad diameter, (D1). The branch pipe dimensions are held constant such that branch pipe diameter, (D2), is half the pad diameter D1, thickness, (T2) is 0.054_*D1 and length, (L2) is 3.0_*D1..

The radial measurements represent diameters at the pad and branch pipe middle faces. Symmetric loading conditions require only one-half of the pad be modeled for finite element analysis. A linear elastic, thin-shell finite element was employed to accommodate computer storage space limitations and the nature of tubular geometry.

The flexibility of the pad, which is a function of pad geometry, improves the energy-absorption ability of the connection. Minimizing the stresses on the wet welds is required to optimize the design of the connection pad for different types of loading conditions. Originally, flexible pad lengths were determined only by consideration of the wet welds allowable static strength. Adding more weld length to the pad compensated for the wet welds degraded properties. Later work determined that several factors should be considered for pad design these include: the maximum Von Mises equivalent stress in the weld (S_W), the maximum Von Mises equivalent stress in the pad (S_P), total strain energy absorbed in the pad (E_P), the ratios E_P/S_W^2 and E_P/S_P^2.

According to linear elasticity, the energy absorbed in the pad is linearly proportional to the square of stress. The maximum Von Mises equivalent stress is different for each loading case. Therefore, it is necessary to use the ratio of the total strain energy in the pad to the square of the maximum Von Mises equivalent stress in order to compare the strain energy absorption for different pads, under the condition of the same maximum Von Mises equivalent stress.

An ideal pad design should minimize S_W and S_P, and have the maximum ratio for E_P/S_W^2 and E_P/S_p^2. However, in practical engineering situations it may be that conditions will not be this straightforward. It is quite possible that these conditions may be in conflict with each other. A trade-off among these four factors may be required. Also, for different service purposes of the connection pad, changes in the optimization criteria may be necessary. Since underwater welding is widely used in the offshore petroleum industry, where the fatigue life is most important, minimizing the maximum Von Mises equivalent stress in the weld is a first priority, followed by maximizing E_P/S_W^2, and then maximizing total strain energy absorbed in the pad under a given loading level. Since the service performance of the pad can be improved by using a higher grade of material, the least priority is placed on those factors related to S_P.

Considering a typical flexible connection pad, which sustains a concentrated bending force parallel to the axis of the main pipe and applied at the end of the branch pipe, Figure 9 shows the maximum Von Mises equivalent stress in the underwater welds as functions of the length to diameter ratio of the pad. Several weld conditions, such as welding along two vertical sides, as well as two different pad thicknesses, 0.084 and 0.04 times the pad diameter were studied.

Reducing the pad thickness significantly increases the maximum Von Mises equivalent stress in the weld (S_W), reducing the pad length to a given level, dependent upon the pad thickness, S_W increases. The weld position has less effect on S_W, compared with the other two factors. Horizontally placed welds exhibited the smallest S_W in the weld for the three weld positions examined.

The position of the weld has a predominant influence on the strain energy absorption in the pad (E_P). Figure 10 shows the effect of pad dimensions and weld positions on E_P/S_W^2 ratio. Horizontally welding the top and bottom of the pad creates a larger E_P/S_W^2 ratio than the other welding positions. This is particularly true when the pad length becomes equal to $3.5 * D1$, the E_P/S_W^2 ratio for the horizontal welds is four times greater than those for the other two welding positions, provided that the remaining variables stay the same. Figure 10 also shows that the E_P/S_W^2 ratio becomes larger by increasing the pad thickness and the height of the pad arc H.

Variations of total strain energy in the pad are illustrated in Figure 11. Maximum strain energy absorption (E_P) occurs when the connection pad is thin and short. For vertically placed welds, a larger E_P value is obtained by reducing the pad length. For the other two welding positions, a larger pad creates a larger E_P value.

By taking all of the above into consideration, and following the previously stated optimization criteria, it is not difficult to determine the optimum pad design under a bending load. The trend is to use a long, thick and large arc height pad, with underwater welds placed at the top and bottom of the pad. For the cases studied, the best pad design is as follows: pad length (L1) = $3.5 * $ pad diameter (D1); pad thickness (T1) = $0.084 * D1$; and the height of pad arc (H) = $0.5 * D1$; the underwater welds should be placed on the top and bottom of the pad.

When the branch pipe is loaded in tension only, in contrast to the bending case, very small stress concentration is observed near the connection line between the pad and the branch pipe. Instead, the Von Mises equivalent stress in the pad always reaches its maximum value in the welds. This is true for all three welding conditions.

Figure 12 shows the relationships between the maximum Von Mises equivalent stress in the weld and the pad length. The maximum Von Mises equivalent stress reaches its minimum value when the pad length is between 1.5 and 2.0 times D1, and the pad is welded horizontally or all around to the main pipe.

Figures 13 and 14 present the effects of pad length on E_P/S_W^2 and E_P. The combination of horizontal welds and a long pad is most desirable for obtaining a high E_P/S_W^2 ratio and E_P value. However, the pad length should not exceed $2.0 * D1$, or the maximum Von Mises equivalent stress will increase rapidly in the case of horizontal welds - Figure 12.

Under tensile loading, the optimum pad length should be 2.0_*D1 and the pad should be welded horizontally. Clearly, this situation differs from the optimum pad design for the bending load. There are many situations where both tensile and bending loads are present at the same time. For these situations, a connection pad of length 2.0_*D1 with horizontal welds would result in low maximum Von Mises equivalent stress in the welds, and a relatively high E_P/S_W^2 ratio and E_P value.

In summary, the optimum dimensions for the length of the pad is 2 times the diameter of the main pipe, thickness is 0.084 times the diameter and arc height is 0.5 times the diameter. The optimum welding positions between the main pipe and the pad are all around the pad.

When the flexible connections are used, the whole structure will also respond to the change of the connection rigidity. Several design elements, such as possible reduction of structural rigidity, change of natural frequency, and increase in structural value requirements, must be considered.

Experimental Verifications

A total of 21 T connections were fabricated under simulated diving condition (*i.e.*, in diving tank). Of this total, six were used for static loading and seven for impact loading. There were four types of tubular T connections varied only in the thickness of the pad, and the regular T connections varied only in that some were welded in the air and some were welded underwater. The fabrication of the pad connections followed the basic design shown in Figure 15. The fabrication of the regular T connections was without the pad.

The T connection parts were cut using an oxyacetylene torch. The 6 in. (152 mm) piping was cut into 11 in. (279 mm) pieces and then sliced longitudinally for two pad pieces. The inside diameter of the Schedule 80 pipe closely matched the outside diameter of the 5 in. diameter pipe and did not require much deflection to force the sides of the pad to touch the 5 in. (127 mm) pipe. The inside diameter of the Schedule 40 pipe is larger than the 5 in. pipe and required more deflection to have a snug fit on the 5 in. pipe. The Schedule 80 pieces were heated slightly to aid in the compression of the pad, and because of the thickness of 0.432 in. (11 mm), it was hard to bend.

The pad was tacked onto the main pipe, and then as the sides were compressed in a vise onto the main pipe, the pad was tack welded four places. After the pad was tacked in place, the 3 in. branch pipe was welded to the pad. The 3 in. (76 mm) piece was saddled and beveled to allow for a full penetration weld. The saddle was custom cut to allow 0.125 in. (3 mm) root opening with a 45° bevel.

This weld was accomplished using an open butt joint. The root and hot pass were welded with 0.125 in. (3 mm) E6010 electrodes, and the fill and cap beads with 3/32 in. (2 mm) E7018. Between the root and hot passes, the weld was ground out and brushed. The remainder of the welds were wire brushed between the layers.

After the T weld was finished, the pad-to-main-pipe underwater welds were made. Each side of the pad was welded with three stringer beads. The top and bottom of the fillet welds were rounded to give a slight end-return. The underwater pad-to-main-pipe welds were fillet welds. The first attempt was made with 0.125 in. electrodes, but more satisfactory results were achieved with 5/32 in. (4 mm) electrodes.

The testing of the flexible pad connections included a static and impact loading condition. The connections for each test were selected by its weld quality. The static loading placed the bottom half of the T in tension, while the impact loading test stressed the top half. Therefore, the regions of the underwater welds with the best quality were selected for the particular test. The goal of the testing is to verify the fitness-for-service and not to see if a defect will cause or add to a failure.

Static Loading

The joints were tested under a static loading condition to compare the strength of the pad and fillet welds to the in-the-air welded structure. The static loading induced both a bending and shear stress. During the first test, the sharp corner edges of the joint gouged into the fixture and the fixture failed by bending under a 140 ksi (623 kN) load. The joint did not bend, because the structure had become as a rigid frame.

A second attempt was made using roller bearings sandwiched between 4.0 × 6.0 × 0.625 in. (102 × 152 × 16 mm) thick machined plates beneath the T joint during loading. This rolling base would allow the ends of the T to move or roll - Figure 16.

Six of the T connections were given a compressive load of 96 ksi (427 kN). None of the connections failed from the loading. The loading condition was two times higher than the calculated yield point of 48 ksi (213.5 kN). The contact points of the T connections were severely deformed, but no plastic deformation of the branch tube at the weld was observed.

Impact Loading

A fixture device was designed to secure and hold a test joint in place while a weight was dropped on the end of the branch tube - Figure 17. The branch tube had a clamped striking pad bolted 11 in. (279 mm) from the main tube. This strike point served to concentrate the impact at the end of the tube. Through calculations, it was determined that four pounds dropped from 6 ft (1.83 m) would cause a plastic deformation in the branch tube of 0.1 in. (2.54 mm). The hypothesis was that if the plastic limit of the tube was reached before the welds failed, then the strength level of the joint exceeded the strength of the material, and the welds passed on a fitness-for-service test.

The first trial joint gave a 0.125 in. deflection with 33 lb (147 N) from 5 ft (1.52 m) in height. In order to achieve greater deflection and see a greater discrepancy between the regular T and the pad concept T, the weight was doubled and raised to 7 ft (2.13 m) high. Each joint was fitted and bolted in place, the distance between the base plate and a gauge mark was measured. The weight was dropped and impacted the tube. It was then lifted off the end of the tube before measuring the deformation.

The weld areas were checked with dye penetrant after testing. None of the connections impact tested showed any surface cracking. However, the plastic deformation from impact loading was higher for the underwater welded T joint than the padded Ts. The completely air-welded T connection had lowest plastic deformation. Figure 18 shows the plastic deformation of various types of T connections from the impact loading.

Upon a macro examination of the weld cross-section, two root bead cracks were noticed in the underwater welded T joint. The top crack traversed one-third of the thickness of the branch tube. No crack was found in the padded joints, nor in the air-welded T joints. These cracks may explain why the deformation from impact was greater than with the padded T. In comparison to the air-welded T connections, the flexible pad caused greater plastic deformation in the padded T.

Summary

The most significant finding of this study was the flexible pad concept for a joint connection. The energy dissipates in the connection pad before it reaches the welds made underwater, and the energy stress in the welds is minimal. The stress in the underwater welds is kept below the endurance limit for infinite fatigue life. The joint performance under impact loading would also be improved. Several other advantages with this connection would include quick installation; little or no fit-up time; better weld quality with fillet welds but not groove welds, which typically are of poor quality in subsea conditions; pre-made parts for ready installation; and viability for new construction or fabrication. This concept appears to be a feasible method of circumventing the expected pejorative consequences of degraded mechanical properties in a connection, maintaining performance limits, and economically benefiting from connections which are less expensive and easier to install.

Through this research on the reduced Type B weld properties and underwater welding, several specific conclusions can be made.

1. Statistically, 11% of Type B welds meet Type A hardness criteria; whereas, 90% of Type B welds meet Type A Charpy V-notch and ultimate tensile strength requirements.

2. The ultimate tensile strength of an underwater wet weld is equal to that of an air weld, but the Charpy V-notch values are reduced to 62% to 75% of equivalent air welds.

3. In a static loading condition, the flexible pad Ts were as strong as the air-welded Ts.

4. The flexible pad Ts displayed more deflection than the air weld Ts, hereby reducing the amount of stress affecting or acting on the welds.

5. The impact stress caused cracking in the underwater welded T, but not the other Ts.

6. For a connection pad sustaining a concentrated bending force parallel to the axis of the main pipe and applied at the end of the branch pipe, its optimum geometry is $L1 = 3.5_*D1$, $T1 = 0.084_*D1$ and $H = 0.5_*D1$, when the diameter of the branch pipe (D2) is half of the pad diameter (D1). The welds connecting the pad and the main pipe should be placed on the top and bottom of the pad.

7. When a tensile force is applied uniformly along the axis of the branch pipe of the connection pad with $D2 = 0.5_*D1$, the optimum pad length (L1) is 2.0_*D1, and the optimum welding positions between the main pipe and the pad are the top and bottom of the pad.

Other DesignResearch

Dally and Fulton[17] investigated the use of the scalloped-split-sleeve (SSS) design for the repair of platform structural braces welded at 33 FSW. Static load axial tension/compression, strong axis bending, and weak axis bending tests were conducted utilizing strain gages. The stress intensity factor was calculated to be 1.8 at the tip of the scallop. A finite element model was developed and the effect of geometric parameters were assessed. It was found that increasing the distance from the scallop tip to the saddle (which adds additional fillet weld length) caused an increase in the hot spot stress at the toe of the weld. This suggested the use of a multi-scallop design that reduces the distance from the scallop tip to the saddle and yet increases the length of the fillet weld and provides additional redundancy to the repair. Subsequent fatigue testing of the single scallop design yielded crack initiation at 24,000 cycles at a hot spot stress range of 66 ksi.

The same program[17] tested a split sleeve repair for pipelines. Mock-ups were welded at depths ranging from 33 to 330 FSW. Hydrostatic pressure testing indicated that in deep welded joints (330 FSW), piping porosity can impact leak integrity. Welds made at shallower depths (< 250 FSW) passed the hydrotest and subsequent burst testing yielded pressures in excess of the calculated design burst pressure.

Summary

In summary, underwater wet welds can be used in their present state for structure repair or construction if a proper design procedure is adopted. The idea is to solve the weld impact problem by reducing the stress in the wet welds through proper design. The wet welding processes currently used by the offshore industries can still be used without any modifications. The wet welded joints will fit for their intended service without compromising the economical advantages.

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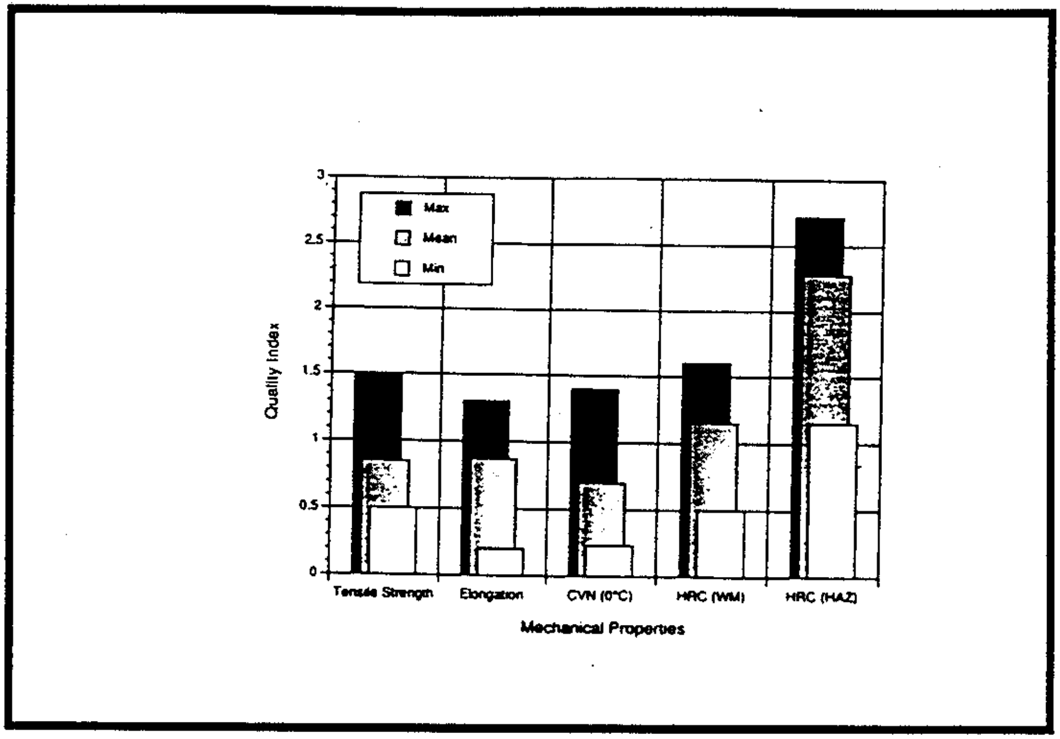


FIGURE 1.
QUALITY INDEX. REFERENCE VALUES OF AIR WELD: TENSILE STRENGTH, 498 MPA; ELONGATION (%), 25; HARDNESS (RC), 18 WELD METAL 25 HAZ

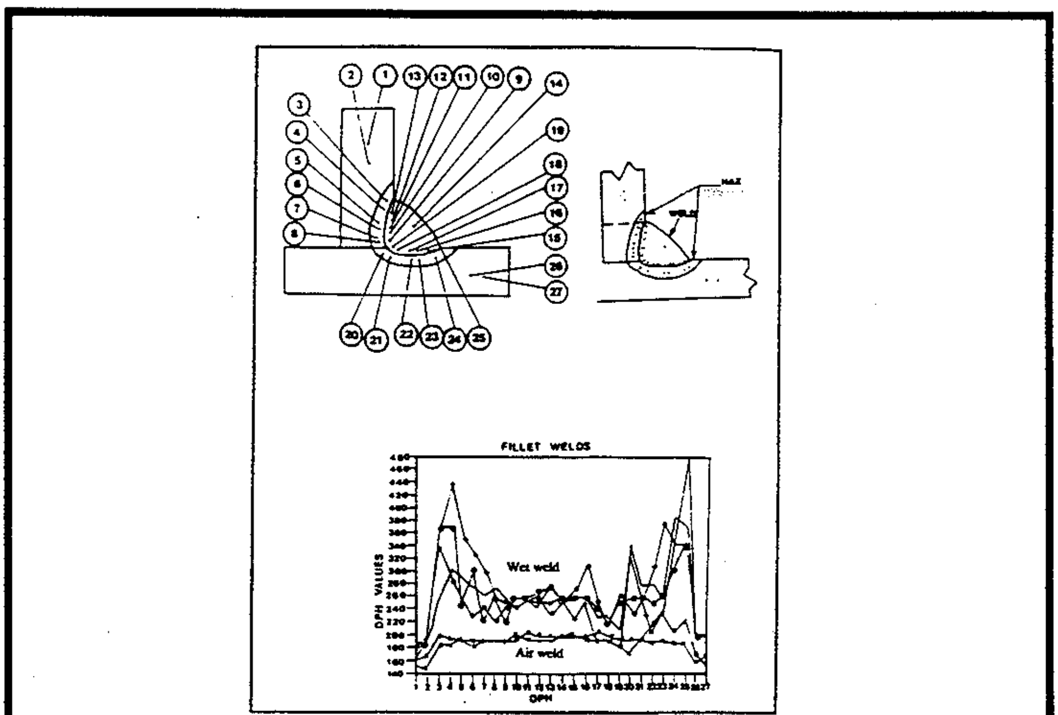


FIGURE 2.
PLOT OF WELD HARDNESS

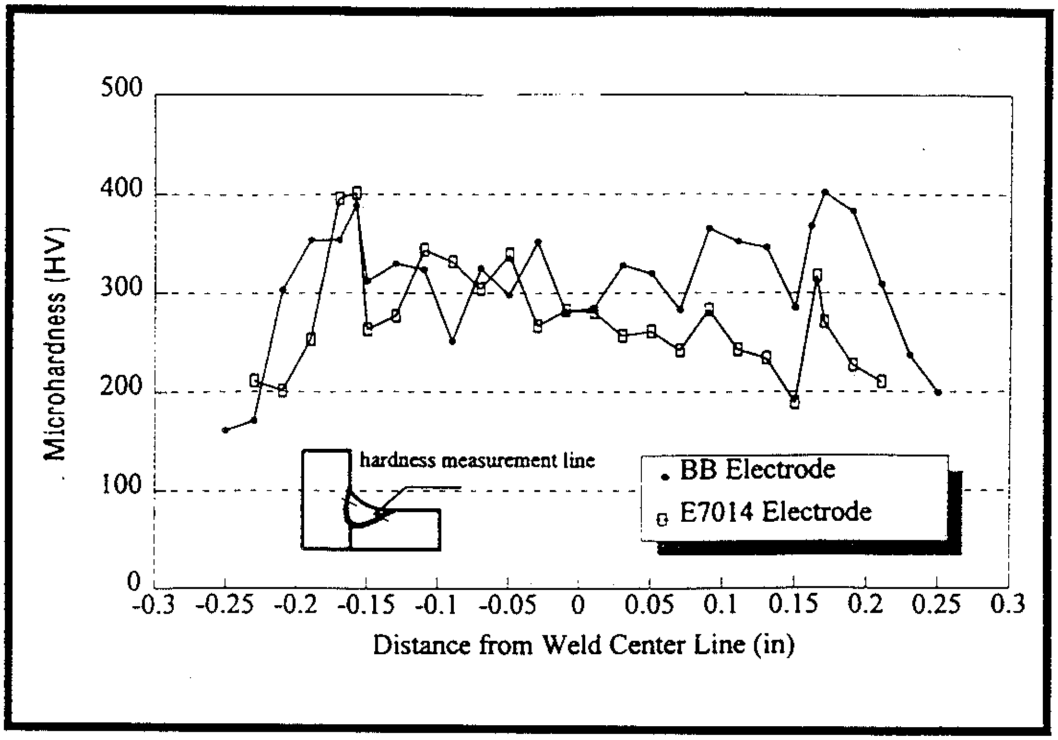


FIGURE 3.
MICROHARDNESS DISTRIBUTIONS ACROSS THE WELDED ZONE
(KNOOP, 100G)

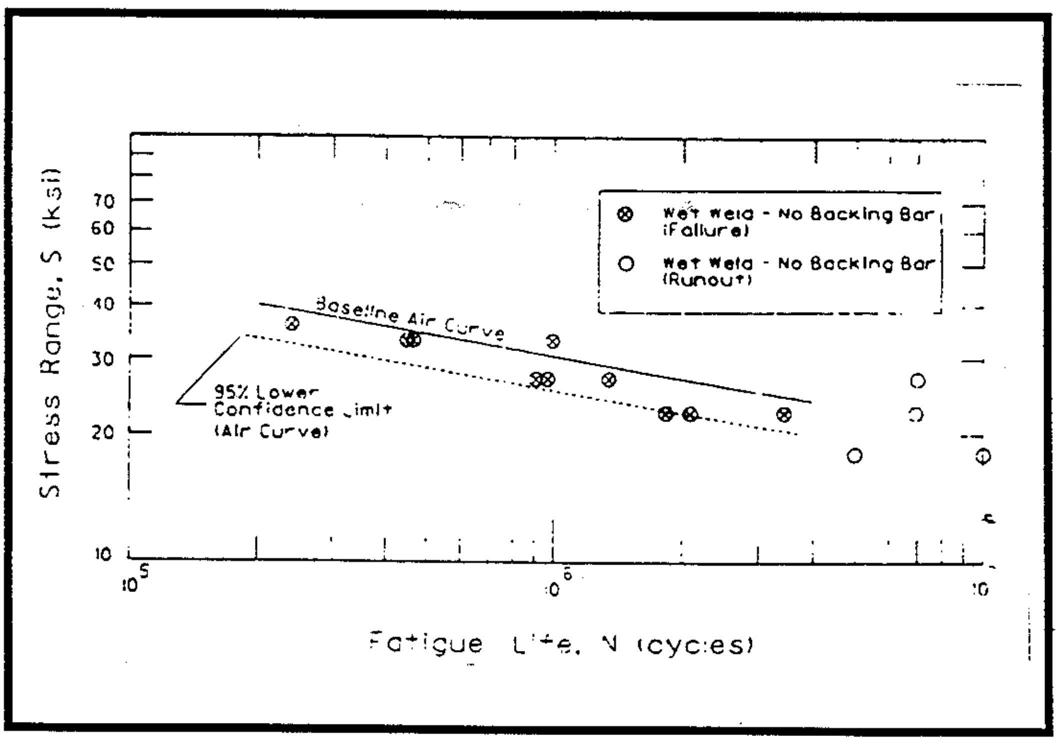


FIGURE 4.
WET WELDED FATIGUE TESTING RESULTS VERSUS
BASELINE S-N CURVE

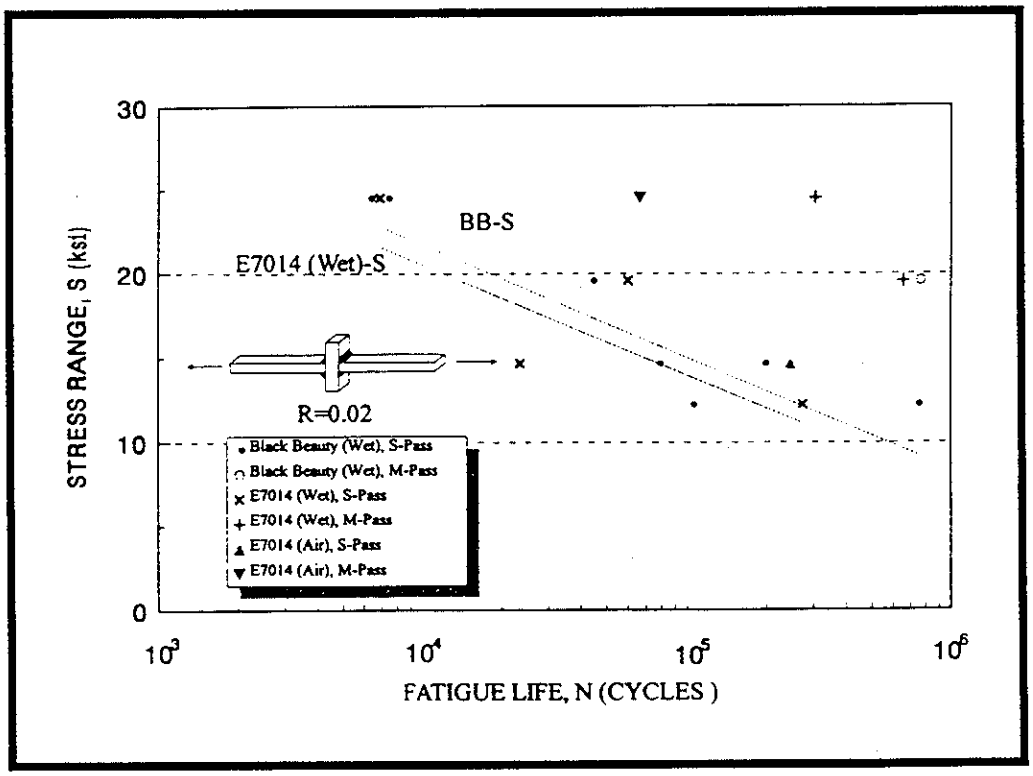
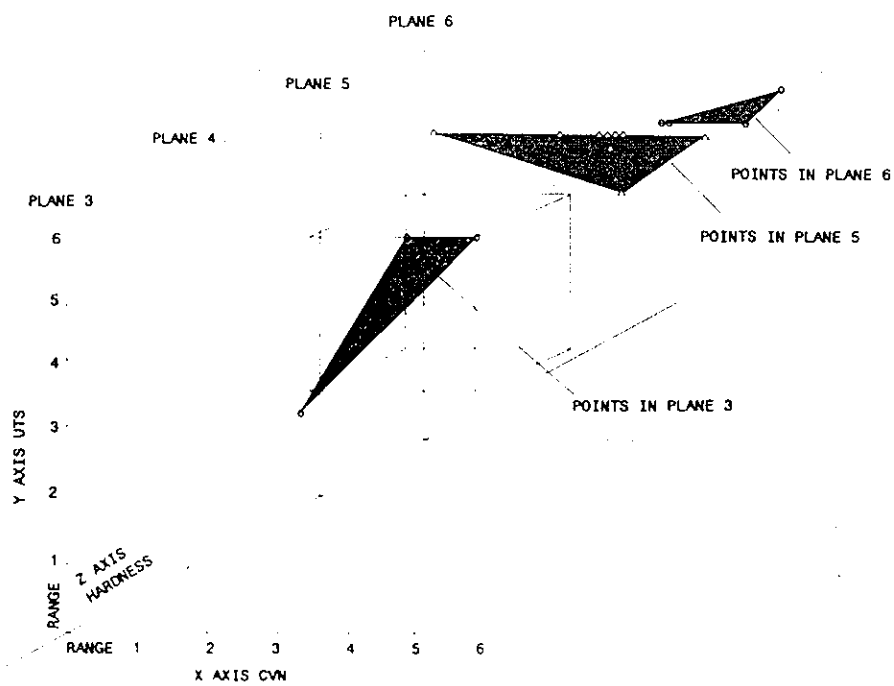


FIGURE 5.
FATIGUE LIFE VERSUS STRESS RANGE



Plane ranges defined by six equal divisions of hardness values

Graph Axis	plane 1	plane 2	plane 3	plane 4	plane 5	plane 6
Z axis (hardness)*	0-80.0	80-160	160-240	240-320	320-400	400-480

* Maximum hardness of HAZ with a 500g load on Vickers:DPH

X and Y coordinates in each plane defined by range divisions of values

Graph Axis	range 1	range 2	range 3	range 4	range 5	range 6
X axis (CVN)**	0-6	6-12	12-18	18-24	24-30	30-36
Y axis (UTS)***	40-46	46-52	52-58	58-64	64-70	70-76

** Charpy impact tests on weld metal at 32°F
***Reduced section tensile tests
Units: CVN (ft-lb) UTS (ksi)

FIGURE 6.
FITTNESS FOR PURPOSE INDEX

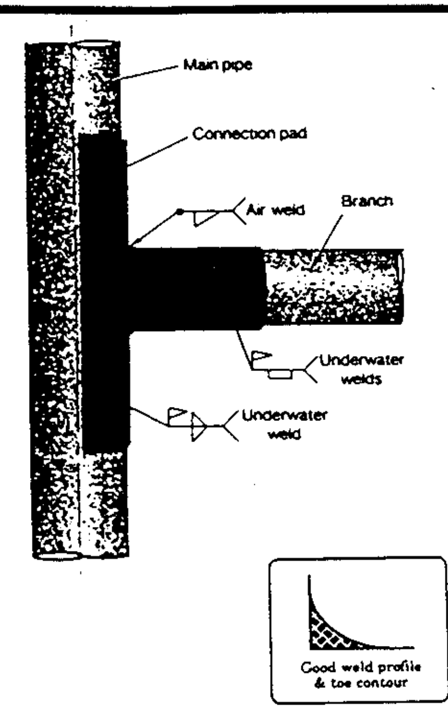


FIGURE 7.
FLEXIBLE PAD CONNECTION CONCEPT

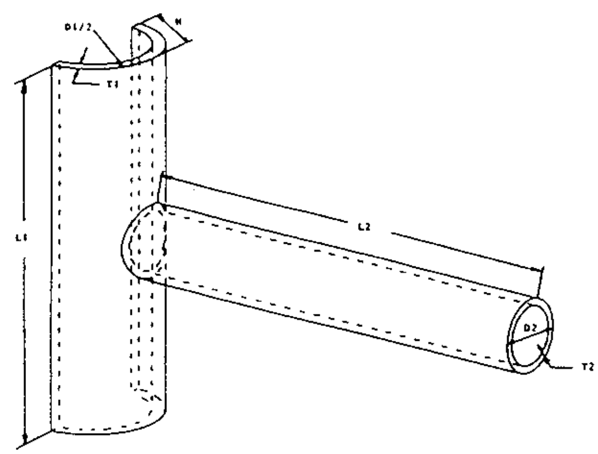


FIGURE 8.
GEOMETRIC VARIABLES OF FLEXIBLE PAD

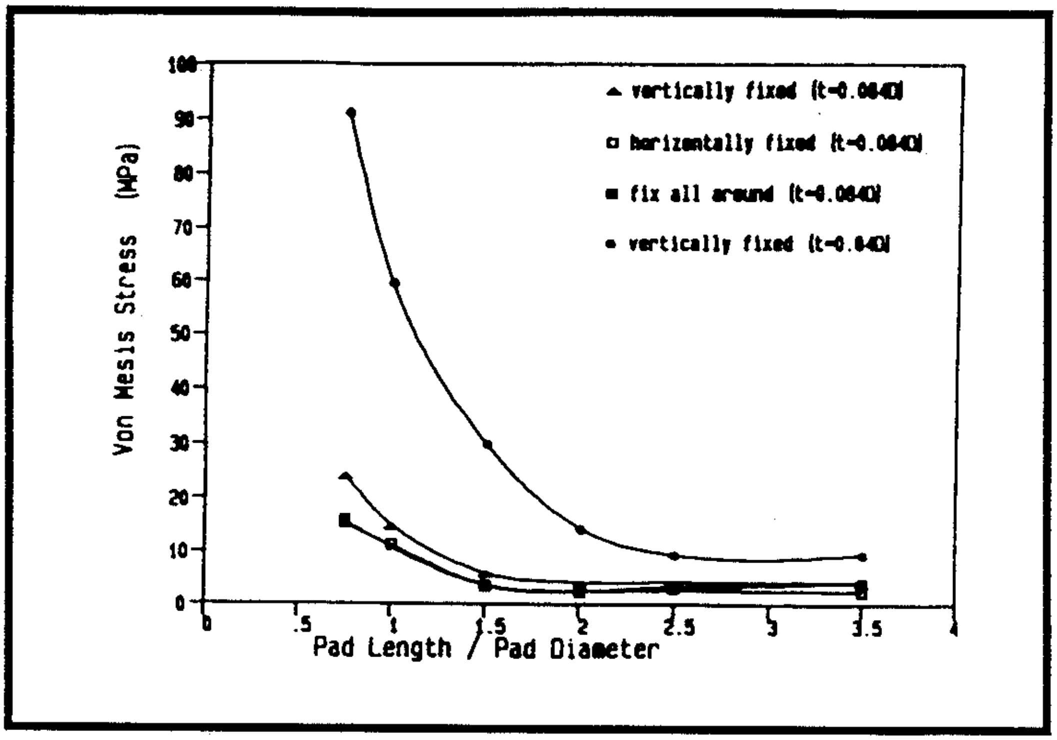


FIGURE 9.
AFFECT OF L1, T1 AND WELD POSITION ON S_W

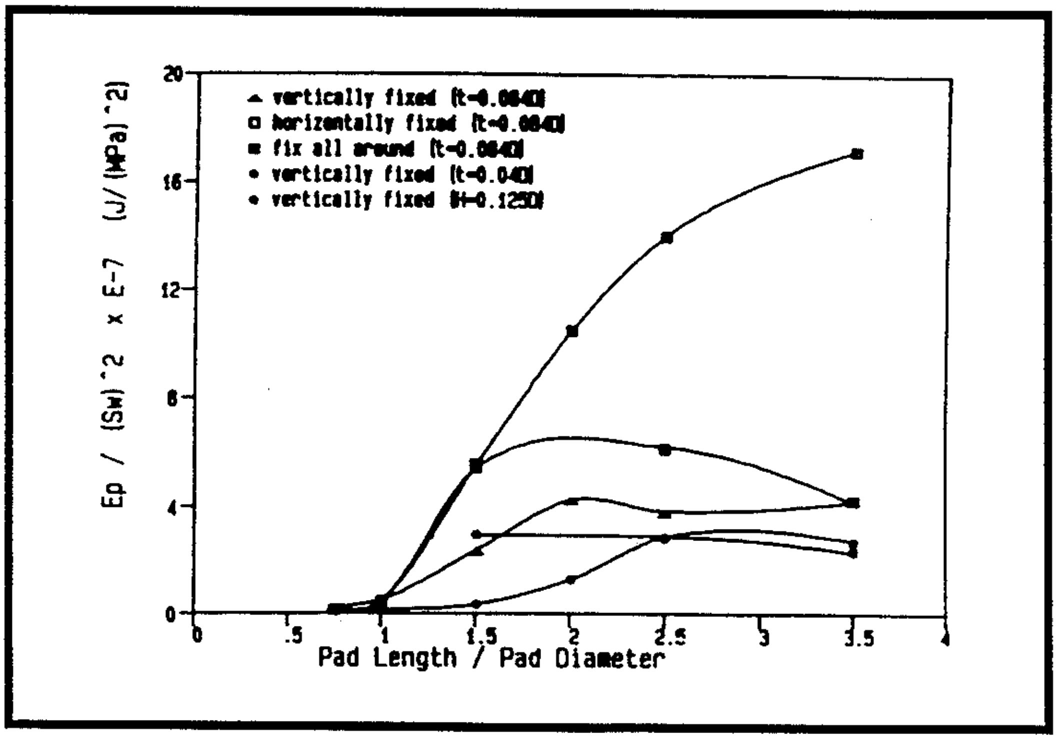


FIGURE 10.
AFFECT OF L1, T1 AND WELD POSITION ON E_P/S_W^2

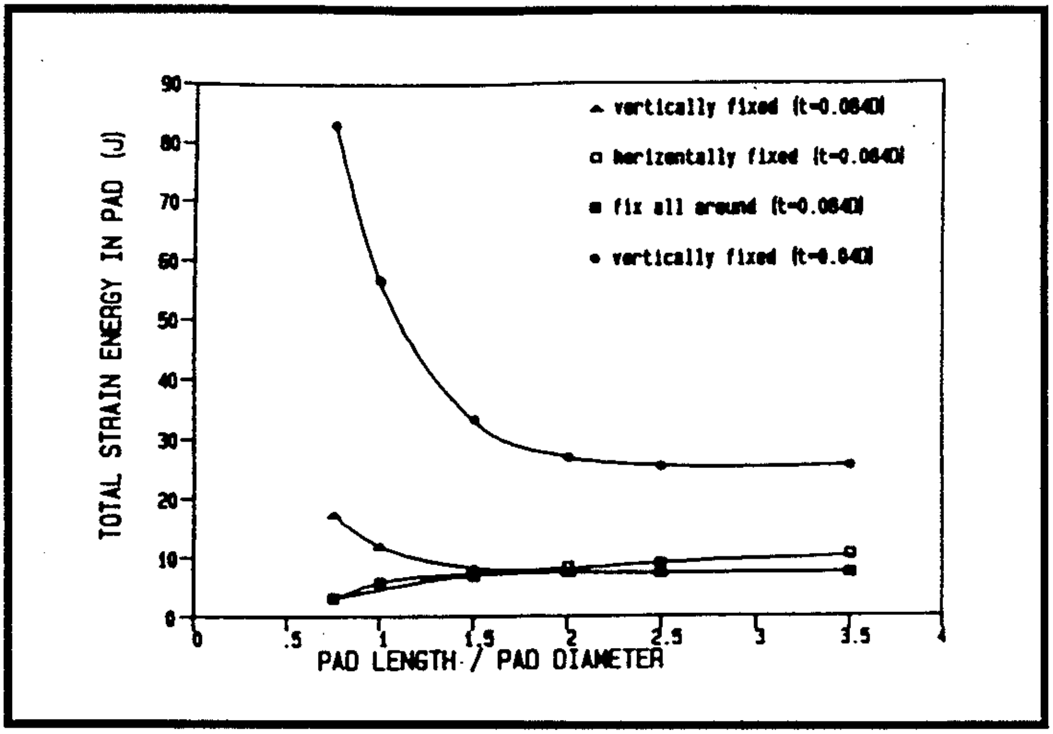


FIGURE 11.
VARIATIONS OF STRAIN ENERGY IN PAD (BENDING)

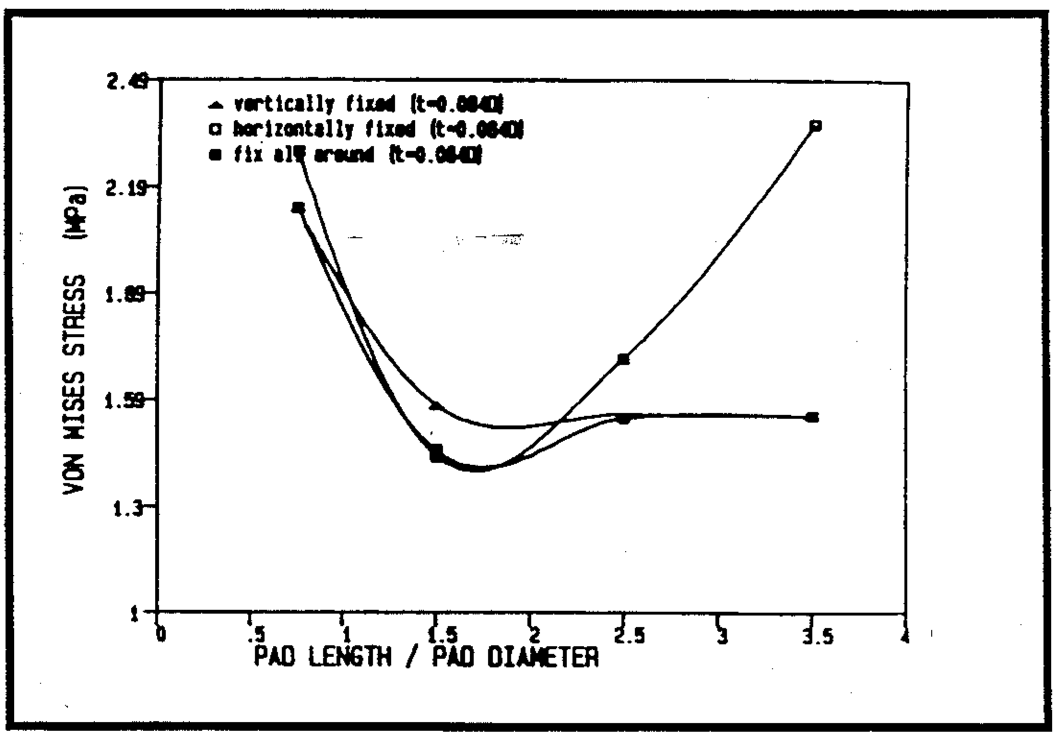


FIGURE 12.
AFFECT OF L1, T1 AND WELD POSITION ON S_W (TENSION)

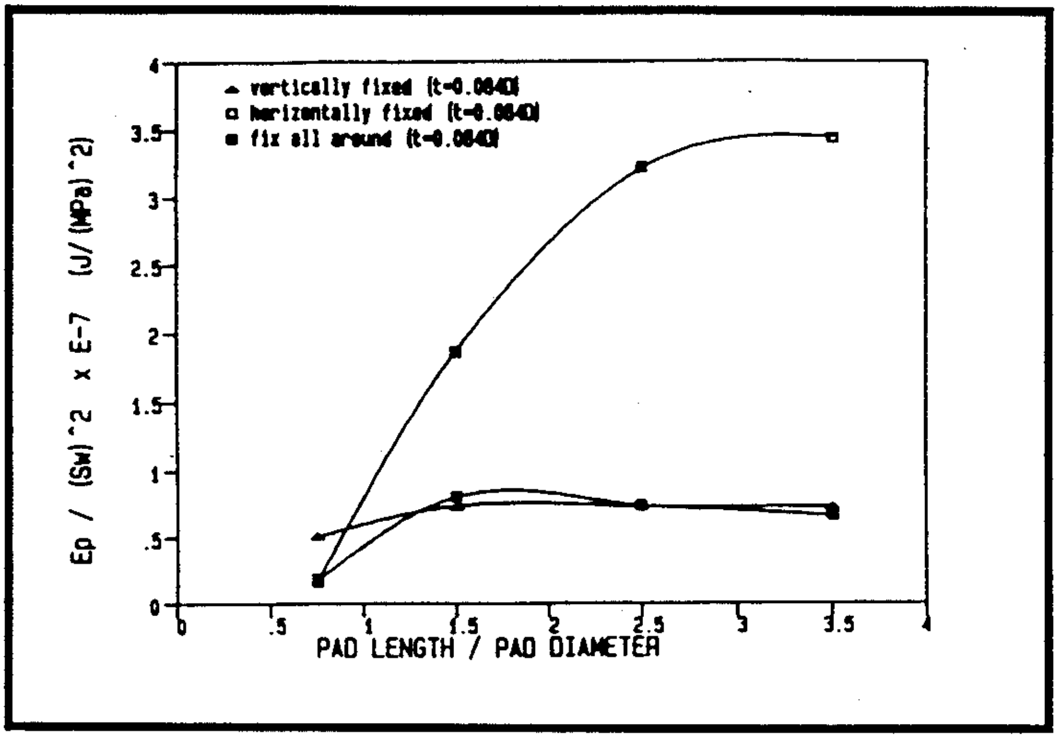


FIGURE 13.
AFFECT OF L1, T1, H AND WELD POSITION
ON E_P/S_W^2 (TENSION)

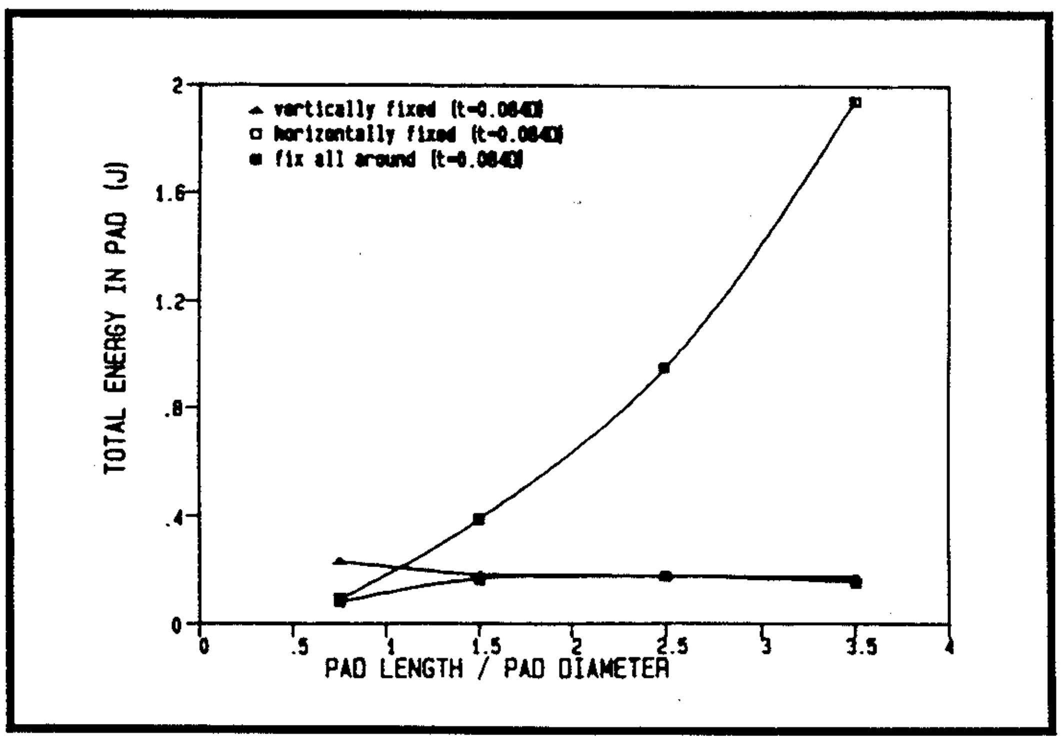


FIGURE 14.
AFFECT OF STRAIN ENERGY IN PAD (TENSION)

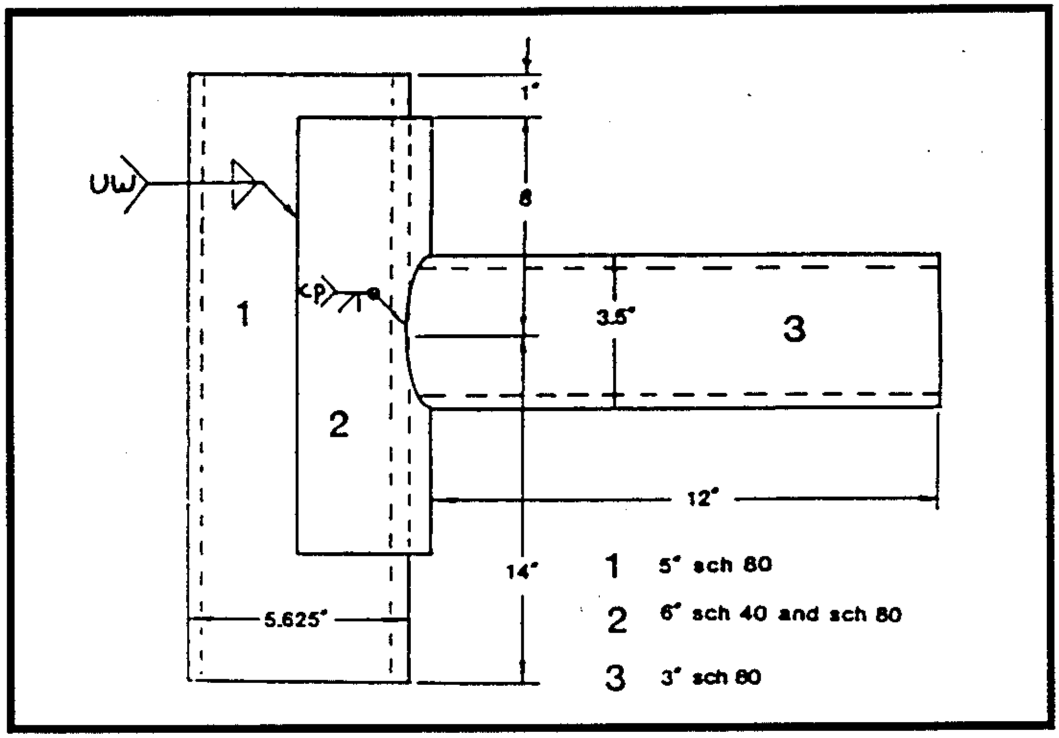


FIGURE 15.
DETAILS OF PAD CONNECTION FOR TESTS

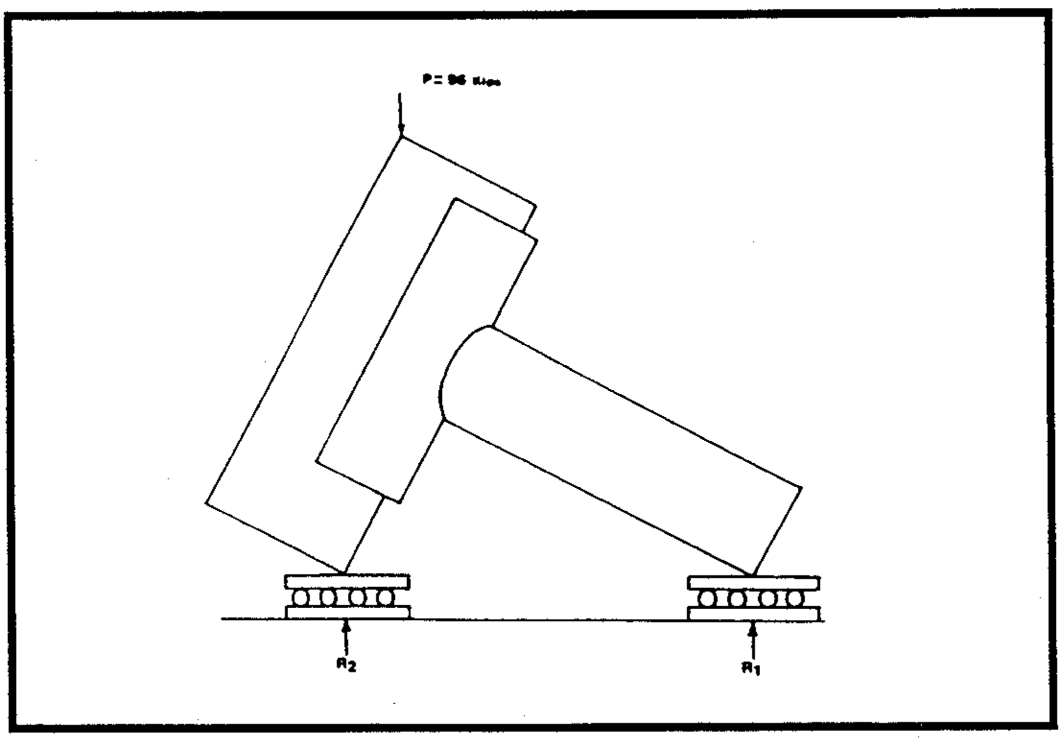


FIGURE 16.
STATIC LOADING OF T CONNECTIONS

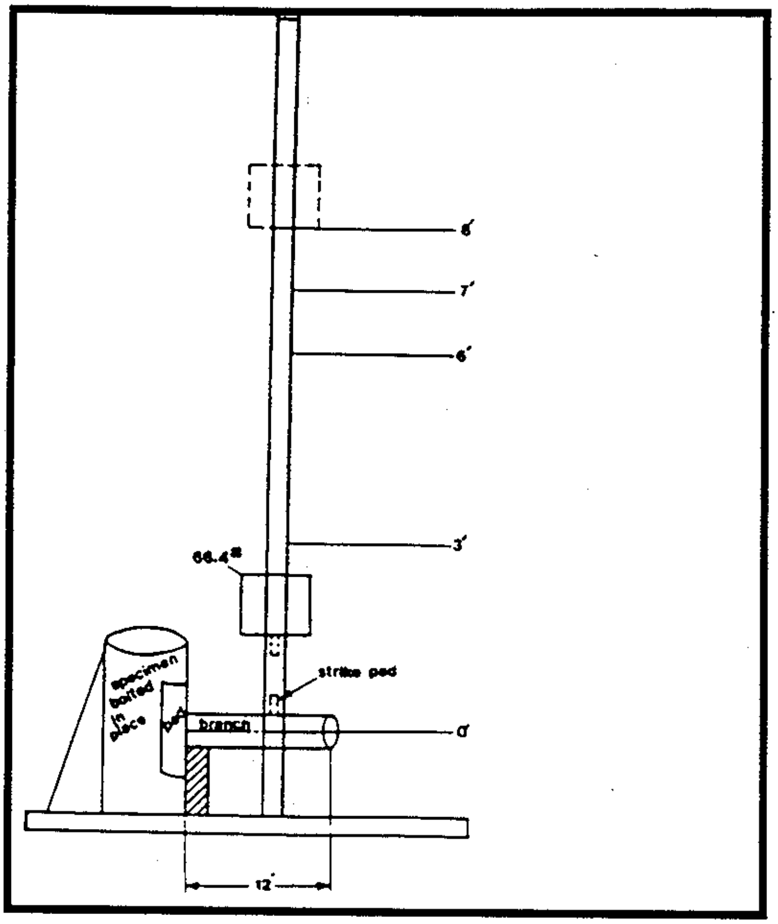


FIGURE 17.
IMPACT LOADING OF T CONNECTIONS

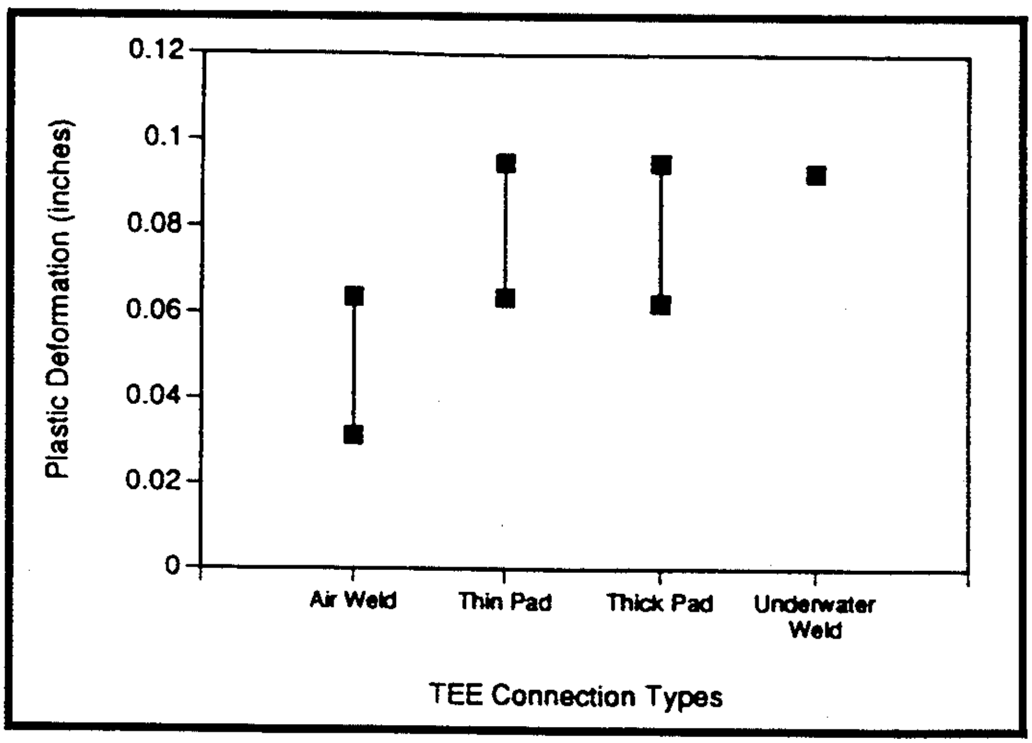


FIGURE 18.
PLASTIC DEFORMATION OF T CONNECTION UNDER IMPACT LOAD

State-of-the-Art and Practice of Underwater Inspection

Michael Craig, UNOCAL Corporation
Larry Goldberg, Sea Test Services

BACKGROUND

Last year the MMS held a similar workshop on platform reassessment and requalification. A 'white paper' entitled "Inspections, Surveys and Data Management" was written by Neal Hennegan, Shell Offshore Inc., Wade Abadie, Oceaneering Solus Schall, Larry Goldberg, Sea Test Services and Walter Winkworth, Lloyd's Register of Shipping. It can be found in the *Proceedings, International Workshop on Reassessment and Requalification of Offshore Production Structures*, December, 1993.

This paper effectively defines the state-of-the-art and practice of underwater inspection of offshore oil and gas platforms. The basic intent of these inspections is to assure the preservation of global structural integrity. There are many guidelines and practices in the above-mentioned paper that are common to the underwater inspection of underwater welded repairs. There is no point in repeating these common issues. There are, however, important developments to identify and issues to highlight that pertain to the inspection of underwater welding, as identified below. The Appendix summarizes some of the recent API developments pertaining to global platform inspections.

Four issues are addressed; inspection frequency, inspection method, inspection quality and data management, in the context of both global structural integrity and localized underwater welding.

INSPECTION FREQUENCY

INSPECTION FREQUENCY - GLOBAL STRUCTURAL INTEGRITY

The frequency and method of inspecting any individual platform should be driven by two primary factors - its economic importance (or failure consequences), and its estimated structural reliability. This will result in a proper focusing of limited resources (of money and time), and avoiding a waste of resources, on inspections that are unnecessary.

The matrix in FIGURE 1 illustrates ~~this~~ concept. Each of the 300 or so OCS platforms in Unocal's Gulf of Mexico fleet has been assigned a relative economic importance ranking (1 to 5, designated by the asset teams), and a structural reliability ranking (1 to 5, designated by the lead author, and related mainly to age). The distribution of platforms within this matrix then allows for the planning of an inspection frequency cycle that reflects each platform's economic and reliability characteristics.
Where the boundaries are drawn, and what frequencies are assigned each group, are a matter of judgment. This is a lot more effective than inspecting each platform by rote every 5 years.

Note the 155 structures - low consequence, high reliability ones - that are assigned a 10-year inspection cycle. By current law (30 CFR 250.142), these structures must be inspected at least every 5 years, or a waiver must be sought from the Regional Supervisor. Waivers will be granted if the production and structural characteristics of each platform are defined, and the MMS agree with their low consequence/high reliability assignations. The MMS granted Unocal waivers on most (but not all) of the 10-year structures submitted, whose last inspections were 5 years old. Platforms with significant repaired damage (some repaired by wet welding) are most likely to be in the medium to high inspection cycle categories.

Once frequencies are set (but always subject to change as changing circumstances demand), then inspections must be prioritized, and inspection method(s) defined. Inspection priorities are:

1. No corrosion flaw: Check that the structure has polarized properly, that there is no ongoing active platform corrosion, and the anodes are not depleted, by cathodic protection checks, anode surveys and visual surveys.

2. No design flaw: Check there is no cracking. Design errors are in large part the cause of cracking (be it in the Gulf of Mexico or the North Sea). Verify by visual inspection and flooded member detection, with possibly magnetic particle inspection (MPI) at selected 'hot spots', as discussed in the 'Inspection Methods' section.

INSPECTION FREQUENCY - UNDERWATER WELDS

The same factors driving global inspections should drive inspections of underwater welds - the consequences of the repair failing, and an estimate of the quality/integrity of the effected repair. API RP 2A[1] recommends that areas which are critical to the structural integrity of the platform, and which have undergone structural repairs, be inspected by level II (general visual) inspection approximately one year following completion of the repair. The frequency (and method) of inspection of underwater welds should be specific to each welding project, and should be determined by a qualified engineer familiar with the function, criteria and implementation of the underwater welds.

INSPECTION METHOD

Three cases are considered; platforms with no inspection record (a few still remain), platforms with (the right) inspection history, and damage/repair inspections. The first two cases relate to global structural integrity preservation, the latter one to localized repair.

INSPECTION METHOD - GLOBAL STRUCTURAL INTEGRITY

No Records: In the authors' opinion, the most effective way of establishing a 'baseline' inspection of a platform with no inspection history is by quality flooded member detection. The intent of a baseline inspection is to develop as comprehensive an understanding of the general structural health of the platform as cost effectively as possible.

Flooded member detection (FMD) of a large number of members allows for this. The detections over a large area of the platform allows for a check on gross damage, in the form of missing members or torn joints. And this is the damage that we are really looking for. Flooded members ends of those members that are structurally significant are then systematically cleaned, visually inspected, and MPI'd as necessary, to establish the cause of the flooding (usually through-wall joint weldment cracking).

In addition, a couple of joint areas should be cleaned locally and the welds inspected visually, to confirm adequate corrosion protection, the primary factor affecting structural integrity. Further, visual inspection with some cleaning is complementary and cost effective to FMD, in a few localized areas in the first horizontal framing level nearest the waterline.

Some Inspection History: Assuming that a platform has undergone a comprehensive baseline inspection as described above (if not, then implement such), the authors believe that the most information/cost effective inspection method is to do a comprehensive Level II fly-by using divers or ROV, with spot cleaning checks described above to confirm corrosion protection.

The intent of the thorough fly-by's is to check for gross structural damage - damage that can be spotted visually, such as missing members and separated or torn joints. The great majority of these platforms - and certainly those that are of high consequence - are redundant. That is, there exist numerous alternate load paths such that in order for damage to significantly affect global structural integrity, it has to be quite significant. Put another way, every missing member or broken joint does not necessarily have to be repaired.

INSPECTION METHOD - UNDERWATER WELDS

Damage: The last statement above has important implications for repair work. Once damage is detected, the engineer must ensure that, first, it cannot be eliminated by shallow or deep grinding. And second, that the damaged element(s) really needs to be replaced. The authors believe that many repairs, including wet welded repairs, have been and continue to be implemented unnecessarily, due to insufficient engineering assessment work. As far as damage goes, every dollar spent on engineering and planning usually saves ten or so dollars in field work.

Gulf of Mexico damage tends to be due to either boat damage or corrosion. Fatigue cracking tends to be limited to the North Sea, and there only in older structures where fatigue was not properly addressed in design. Fatigue is rarely a problem in the Gulf of Mexico.

Once repair is deemed necessary (in the form of either member replacement, dent repair or joint cracking repair), firstly, the choice of mechanical (clamping) versus wet welding must be made (note, hyperbaric welding in a habitat is an option that will rarely be cost effective). The choice between wet welding and clamps is unclear, since the engineering community is divided on the reliability of wet welded connections.

Underwater welds are commonly fillet welds and therefore subject to primarily visual and magnetic particle inspection methods. Other inspection methods being used to a lesser degree include ultrasonic examination, radiography, the use of the acoustic field measurement device (ACFM) and eddy current. If the circumstances are right, remote (acoustic) monitoring of critical weldments may be used. This may avoid the repeated use of divers to monitor/inspect the health of particularly critical subsea welds in non-redundant structures. It may also frighten the user to death.

INSPECTION QUALITY - GLOBAL AND LOCAL

First, the resulting quality of an underwater welded repair is the result of a team effort between designer, welding operator and inspector. It is vital that for high quality repairs these different parties work together from the start of a repair project as a team. The team can greatly improve the quality of the underwater welded repair if:

1) the base metal is of good quality (ideally low Carbon Equivalent, high toughness, with through thickness properties),
2) the wet welding repair procedure specification and procedure qualification are derived and made with coupons of the base metal (and they include the use of an appropriate electrode),
3) there are good as-built dimensions (good fit-up is crucial),
4) the design includes doublers, no groove welds, no overhead welds, stringer beads (no weaving), scallops (for smaller but longer welds to minimize hydrogen build-up), and rounded corners (to allow smooth, continuous deposition of weld metal),
5) the diver/welder, and inspector, are properly qualified, and
6) the repair work is shallow, but not so shallow as to be near or at the waterline. This criterion is often not met, and is one primary reason for clamped repair - damage generally tends to be near the waterline.

Quality in engineering, operation and weld inspection are essential, especially when repair is necessary, and wet welding is the repair method of choice. Taking each in turn:

Engineering: First, both the annual subsea inspection program of a company's fleet of platforms as well as individual repairs, must be planned by a *qualified engineer* - someone who understands redundancy, safety factors and failure consequences. The results of the inspections, again, must be assessed and acted upon by a qualified engineer. This engineer must judge what the MMS mean by 'minor' damage and 'major' damage, in the absence of definition or guidance. This is no mean task. If damage repair is deemed necessary and to be repaired by wet welding, then it is crucial that the engineer make his design as operator (welder) friendly as possible. See the list above. In making that design, he must decide what loads to apply - section 17? Original? 20th edition? And what weld allowables to use - 100% of in-air allowables? 50%? Again, no easy task.

Operation: It is very important that for any subsea NDE inspection work - be it flooded member detection or MPI - that the diver/inspector be *qualified*. Several attempts by the second author to stimulate industry, ASNT, ABS, AWS et al. into developing a NDE diver qualification requirement has not been fulfilled. Significant difficulties can be created by an unqualified diver performing NDE work[2]. The need for proper qualification of the wet welder is more clear and equally as crucial. The integrity of the completed wet weld is highly dependent on the skill and experience of the diver/welder.

Weld Inspection: Critical underwater welds should be inspected by a qualified, third party inspector. API and AWS practices spell out inspection methods for the types of welds used (AWS D1.1, API RP 2MP (draft) for MPI, RP 2X for U/T). It must be realized that the welding inspector is judging weld quality at a distance - through voice and video communication with the diver. He must judge the quality of the weld through images, and not by direct visual examination as is possible with in-air welding. This means that the inspector must be trained in and comfortable with this 'at a distance' inspection method. The need for a *qualified* inspector is evident. The AWS D3b Subcommittee is presently working with the AWS Q&C Committee on a supplementary CWI examination for underwater welding inspectors, for inclusion in the next edition of the D3.6 Specification. The need for *high quality topsides imaging* is also evident. Beware of a potential conflict of interest, especially on critical wet welds. The diving contractor may have troubles in the completion of a wet weld (lack of fit-up, for example), which he may not want to share fully with the client, when reporting the quality of the completed weld. Again, the use of a qualified, independent inspector should be considered, where circumstances merit.

DATA MANAGEMENT - GLOBAL AND LOCAL INSPECTIONS

The large quantity of inspection data - inspection reports, damage logs, repair logs, photos, videos - must be effectively managed, that is, made easily retrievable, preferably in the context of other related information. The technology is available to gather inspection data real time, scan drawings and reports into digital format, and integrate this information into one database that includes the structures' original design, fabrication, and installation files, as-built drawings, and in-service inspection history. We are not doing enough to capitalize on this technology. These comments apply to both global as well as local inspections.

APPENDIX

Some useful changes have been drafted for inclusion in Section 14 SURVEYS of the next edition of API RP 2A. All changes are along the lines of what is discussed above. These changes include: Inspection program planned by a qualified engineer; corrosion monitoring supervised by qualified personnel; clarification of a Level I drop cell survey, and an emphasis on its importance; the use of flooded member detection; cracks can be monitored (and not always repaired); inspection frequencies as a function of failure consequences; the potential need for a Level II inspection after boat damage or dropped object impact; and Level II inspection frequencies can extend to 10 years, depending on failure consequences ('exposure category').

Once adopted at the end of this year, the current Section 14 will encourage compatible changes to the CFR requirements.

REFERENCES

1. American Petroleum Institute, "Recommended Practice for Planning, Designing and Constructing Fixed Offshore Platforms - Working Stress Design", API RP 2A-WSD, 20th Edition, July, 1993.

2. Craig, M. J. K., Dolan, D. K. and Hopper, D. M., "Rehabilitation of a 96-slot Platform", *Proceedings, Offshore Technology Conference*, OTC 7147, May, 1993, Houston, TX.

UNOCAL GULF OF MEXICO OCS PLATFORMS

CONSEQUENCE, RELIABILITY & INSPECTION CYCLE MATRIX

CONSEQUENCE RANK

high … *low*

STRUCTURAL RELIABILITY RANK		1	2	3	4
low	5	14	4	14	32
	4	6	3	4	21
	3	9	2	9	13
	2	25	18	20	29
high	1	15	9	5	10

STRUCTURAL RELIABILITY RANK:

HIGH = Designed to recent criteria, and no structural damage.

LOW = Designed to early criteria, with minor damage.

CONSEQUENCE RANK:

HIGH = Significant life safety, environmental, and economic consequences.

LOW = Minimal life safety, environmental, and economic consequences.

■ = High Inspection Frequency (every 3 years)

▒ = Moderate Inspection Frequency (every 5 years)

□ = Low Inspection Frequency (every 10 years)

FIGURE 1

Theme Paper Number 6

CASE STUDIES OF SUCCESSFUL UNDERWATER WELDING REPAIR

Coordinated by:

Mr. Ron Dennis - Chevron

Inspection, Assessment and Repair of Damaged Offshore Platforms
- D.R. Cayll and J.A. Marino, Chevron

Hurricane "Andrew" Damaged Platform Repaired by Wet Welding
- A.J. Maghes, Panhandle Eastern; T.J. Reynolds, Global; and R.L. Smith, CBS

Inspection, Assessment and Repair of Damaged Offshore Platforms

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ABSTRACT

Chevron U.S.A. Inc., with 1,050 active caissons and platforms in 1992, is the largest operator of offshore platforms in the Gulf of Mexico. With these structures come the responsibility to assure the continued structural integrity of each caisson and platform. For this purpose, Chevron has in place an extensive annual underwater inspection, assessment and repair program, which involves the inspection of 100 to 200 caissons and platforms. In the summer of 1992, Hurricane Andrew tracked through the South Timbalier, Ship Shoal, and Eugene Island Areas of the Gulf of Mexico, exposing approximately 500 of Chevron's caissons and platforms to severe environmental loads.

After post-Hurricane Andrew underwater inspections, Chevron determined that nine of its offshore platforms would require repairs. The required platform repairs ranged from the wet welding repair of a crack in a vertical diagonal member to the removal and replacement of five vertical diagonal members. The objective of this program was to repair the affected members with the least interference to normal production operations and restore the structural integrity of the subject platforms.

The repair program was based on the team concept with Chevron and its contractors participating equally in the design, planning and execution of the repairs. The planning meetings held with the selected contractors served as the primary team forum, with many innovative ideas being formed for these repairs. Each repair was approached individually, being analyzed and assessed, and a plan developed to address each specific repair. All of the repairs incorporated the use of underwater welding. The joint effort between Chevron and its contractors, with the planning meetings to determine the course of action, and allowing sufficient preparation time led to the successful completion of the work.

INTRODUCTION

In the summer of 1992, Chevron U.S.A., Inc. had 1,050 active caissons and platforms in the Gulf of Mexico, of which 790 lay in the Federal Outer Continental Shelf. Of these platforms, 198 were single-well caissons, 127 were single-well tripod structures, and the remaining 465 were 4-pile or larger drilling and production type structures, in water depths from 7 to 682 feet. In accordance with regulations promulgated by the Department of the Interior, Mineral Management Service (MMS), Chevron U.S.A. conducts an underwater inspection program that includes from 100 to 200 caissons and platforms each year. In 1992, Chevron's inspection program consisted of approximately 100 underwater platform inspections.

After completion of this inspection program, Hurricane Andrew came through the Gulf of Mexico on August 26, passing through the South Timbalier, Ship Shoal, and Eugene Island Areas and making landfall southwest of Morgan City, Louisiana. In the aftermath of Hurricane Andrew, the MMS designated a zone 35 miles southwesterly and 50 miles northeasterly of the storm track as an affected zone. The MMS designated 85 mile wide Hurricane Andrew Affected Zone in the Gulf of Mexico OCS included approximately 500 of Chevron's caissons and platforms.

As a result of Hurricane Andrew, Chevron lost a total of two caissons and three platforms in the South Timbalier and Ship Shoal Areas. Later, after the post-Hurricane Andrew underwater inspection, two additional platforms were condemned by Chevron. A total of 13 platforms with damage were required to be assessed for repair recommendations. As a result of Chevron's damage assessment, ten platforms were determined to require repair for continued use.

UNDERWATER INSPECTION PROGRAM

Chevron's Underwater Inspection Program adheres to the recommended practices as outlined in API RP 2A, latest edition, Section 14, SURVEYS, to accomplish requirements as set out by the MMS. After Hurricane Andrew, Chevron mobilized construction and inspection crews to begin assessing the amount of damage caused by the hurricane and to begin the task of repairing any damage found. The underwater inspection portion was undertaken using four individual inspection crews on four individual dive vessels. The initial approach was to perform Level II inspections on platforms that gave some indication above the waterline of having been damaged. Shortly after the program was underway, one of the vessels was re-configured to perform Level III and IV inspections on more severely damaged platforms. The level of underwater survey performed was dictated by the type and amount of damage being found.

Subsequent to these inspections, Chevron conducted post-job meetings with the inspection contractors in an effort to determine more economical and efficient methods of satisfying our inspection requirements. Prior to this, any member that appeared dented, bowed or otherwise compromised had its end-connections grit blasted to "white metal" and given a detailed visual inspection and possibly a magnetic particle inspection (MPI) to determine if any cracks existed. As a result, this procedure has been modified such that any member that appears compromised, as described above, is non-destructively tested using the flooded member detection technique. This equipment is now maintained on board to complement our level II equipment. Although the daily equipment cost is slightly increased, it allows for quick analysis of the members tested, precludes the need to clean and MPI non-flooded members and ultimately reduces the overall cost of the inspection program.

UNDERWATER DAMAGE ASSESSMENT PROGRAM

Chevron's Underwater Damage Assessment Program consists of essentially two phases, a qualitative engineering evaluation and a quantitative engineering assessment. In this first phase, the Underwater Inspection Coordinator and the Damage Assessment Coordinator review all of the damage reports received from the underwater inspection program. A subjective assessment is made of each reported damage using engineering judgment and experience as to the severity of that damage and its possible effect on the structural integrity of the subject platform.

In assessing the severity of the damage, the effect of the damage on the integrity of the member is first considered. Second, if the integrity of the member is judged to be jeopardized, the consequence of the failure of that member to the integrity of the platform is considered. This will include an evaluation of the platform design and its degree of redundancy. The possible effects of a damaged member on the attaching members will also be considered. Lastly, the consequence of all of the member damage and the failure of those members judged to be at risk will be considered on the structural integrity of the platform. If the structural integrity of the platform is considered to possibly be at risk as a consequence of any or all of the member damage on a platform, the damage is considered major damage at this point and a quantitative assessment will be performed.

For the quantitative assessment, Chevron has developed a decision making procedure for the repair of underwater damage. This procedure documents the increasingly rigorous analyses required for the assessment and justification for not making a repair. Figure 1 illustrates this process. The damage assessment procedure begins with the determination of the design environmental load conditions and a linear elastic analysis of the intact platform. The actual forces and moments in the damaged members during the design condition are obtained and the ultimate capacity of the inplace damaged members are determined using the DENTA II program. The ratio of these two values is evaluated against a required Factor of Safety equal to 2.0. This determines whether the integrity of the member is jeopardized.

If the member is in jeopardy, the effect of that member failure is evaluated on the remaining structure during the design condition. In this analysis, those members in jeopardy are removed from the intact structure model and a linear elastic analysis is performed. The effects of the member failures are determined on the remaining structural members and if necessary, overstressed members are checked for its Factor of Safety against failure. At this point, depending on the severity of the damage, another analysis option exists in the form of a non-linear ultimate strength analysis of the platform to determine the effect of the damage on its structural integrity. Generally in the Gulf of Mexico, it is not necessary to perform an ultimate strength analysis for the assessment of damaged members on a platform. The earlier analyses quickly show whether the repair of a damaged member will be required.

UNDERWATER REPAIR PROGRAM

Damage found during the 1992 Summer and post-Hurricane Andrew underwater inspection programs requiring repair consisted primarily of compression buckling failures of members or fatigue type cracking and tension tearing originating in weld heat affected zones (HAZ). Figure 2 summarizes the repairs made in Chevron's 1993 repair program. Repairs made at four of Chevron's platforms, including South Timbalier 151 Production 1, South Timbalier 134 W, South Timbalier 151 J, and South Timbalier 135 M, which are representative of repairs made during the 1993 repair program are presented here.

In proceeding with the repair work required on these platforms, Chevron implemented a team based concept, where the contractor and Chevron would work together equally to develop optimum methods and procedures for each repair. This team process was used both in preparation of repair proposals from selected contractors and in determination of the specific repair methods after selection of the contractor for each platform repair was made.

After assessing the damage found at each platform and estimating the cost of each repair, the economic viability of each platform was evaluated. This economic analysis determined whether the costs of the required platform repairs were justified by the remaining useful economic productive life of the platform. As a result of this economic analysis, one platform, installed in 1960, was condemned rather than be repaired. A total of nine platforms were determine to be economically viable and would be repaired.

Chevron's 1993 repair program for these nine remaining platforms consisted of member and joint repairs in water depths ranging from (-)8 ft. to (-)139 ft. It was realized that a number of these structures would not likely be able to withstand another hurricane without being repaired. Two contractors, Global Divers and Contracting, Inc. and Oceaneering International, Inc., were selected to accomplish these repairs in the shortest time period possible. With the repair program including repairs at eight individual platforms spread over a wide area and extensive repairs at the ST 151 J platform it was decided that Global would perform repairs for the eight individual platforms and Oceaneering would perform the repairs at ST 151 J. This would allow for completion of the platform repair program within a 30 day period.

Welding Procedures and Diver Welder Qualification

Underwater welding procedures and welder qualifications were conducted in accordance with the American Welding Society "Specification For Underwater Welding" ANSI/AWS D3.6-93. Global Divers and Contractors' underwater welding procedures and diver welders were pre-qualified on the basis of previous qualified welding procedures and welder qualifications from similar work performed for other customers in the previous six months. Oceaneering's diver welders were tested in an offshore environment similar to the platform repair locations.

REPAIRS

After selection of the contractor for each platform repair and determining the required repair method for each, the contractor mobilized an inspection crew to visit and reinspect each platform repair location. During this inspection, the contractor would clean and inspect beyond the damaged areas indicated on the original inspection report, MPI test to locate and mark all cracks extending from the damage, dimension check all node members, photograph the damage, perform UT thickness testing to determine the weldability of the damaged area parent metal and take measurements of the member geometry for the onshore fabrication of the replacement members and weldment design.

South Timbalier 151 Production 1

South Timbalier 151 Production 1 platform is an eight-pile platform installed in 1967, in 140 feet of water. This platform is the main central production platform for the ST 151 field, in a four platform complex. The repaired damage on this structure consisted of two damaged vertical X-braces and a K-brace joint. The damaged vertical X-braces were between the (+) 14' Plane A and (-) 26' Plane B jacket framing planes and located in either end of the platform jacket in the transverse Row A and Row D. Damage to these two X-braces was a result of severe compression of the center X-brace joint, resulting in a local buckling failure of the through member on the Row A brace and a 3 1/4" long longitudinal crack in the through member originating in the weld HAZ at the weld toe on the Row D brace. The damaged K-brace joint was located at the (-)26' Plane B elevation in Row A. Damage to this K-brace joint was indicated as a 53" long crack, originating near the weld HAZ of one of the vertical diagonal framing members and progressing along and around the through member towards the other vertical diagonal framing member.

The damaged X-brace repair on Row D consisted of replacing the X-brace framing members with a single vertical diagonal member. Figure 3 illustrates this repair. The entire 16" OD X-brace was removed with a single 4 ft. long member stub left at the lower (-)26 ft. elevation and a single 2 ft. long member stub at the upper (+)14 ft. elevation. The remaining two members were cut-off with a maximum stub length of 4". An adjustable 18" OD x 0.750" oversized replacement VD member fitted with a 20" x 0.812" slip-sleeve was stabbed over the lower 16" OD member stub. The weld preparation on the lower end of the replacement VD member was internally beveled to match the contour of the 33" OD leg to which it was fit. With the aid of two padeyes to assist in positioning the replacement VD was adjusted for proper fit-up. The replacement VD was fitted with an 1" NPT pipe collar and diaphragm plates sealing off each section of the 18" OD replacement member. This allows in cases of difficulty for an air or water source to be connected and aid in extension of the member. No difficulty was encounter here and the upper section of the member was extended with the use of air tugger on the platform connected to a padeye on the upper section.

The lower end of the replacement VD was wet welded with a 3/4" fillet weld. Additionally, two 3" wide x 16" long slots were in this lower end of the member located at the 2 o'clock and 10 o'clock positions to minimize the interference of the gas bubbles escaping the weldment. These slots were wet welded with 3/4" fillet welds to complete this end connection. The upper member end section was dry welded with a full penetration groove weld to the 33" OD leg. The upper free end of the 20" OD slip-sleeve was then dry welded with a 3/4" fillet weld to complete this X-brace repair.

The damaged X-brace repair on Row A consisted of arresting the crack growth and reinforcing the X-brace joint across the through member. To determine whether the crack was through thickness a UT test was performed to determine whether the member was flooded. The crack was determined to be through thickness and the ends of the crack were drilled with a 1/2" diameter hole to arrest any crack propagation. To reinforce this joint, two 6 ft. lengths of 6" x 6" x 1" angle sections were designed and installed on each side of the X-brace joint to bridge over the crack from each connecting member. This angle was wet welded with 3/8" fillet weld at a water depth of approximately (-)8 ft. to complete the repair of this X-brace. Figure 4 illustrates this repair.

The damaged K-joint at the (-)26 ft. elevation was reinspected with MPI and a linear indication was confirmed. However upon closer observation by the inspection diver superintendent, a surface flaw in the steel plate was suspected. This linear indication was ground down 1/16" and the area retested with MPI. No linear indication was then evident and further repair of the joint was not necessary.

South Timbalier 134 W

The South Timbalier 134 W platform is a six-pile platform installed in 1981 in a water depth of 142 feet. This platform is a satellite production platform supporting three wells. The repaired damage on this structure consisted of one buckled vertical diagonal. The damaged A1-A2 VD member, from (+)13 to (-)31 was buckled in two locations along its length, in the center where the buckle failure was located on the underside of the member and at the lower node on the topside of the member. The proposal made by Global for this repair, and accepted by Chevron, was to remove and replace the damaged 22" OD VD member with an adjustable 24" OD x 0.500" oversized replacement VD member fitted with a 26" OD x 0.875" slip-sleeve for installation. Figure 5 illustrates this repair. The damaged VD member was cutout leaving a 2 ft. stub at the (+)13 ft. elevation and a 6 in. stub at the (-)13 ft. elevation. This greatly assisted in the fitup of the new VD member. Similar to the repair work described at ST 151 Production 1 platform, the replacement VD was stabbed over the lower stub. The weld preparation on the lower end of the replacement VD was internally beveled to match the contour of the 40" OD leg joint can to which it was fit. With the aid of two padeyes to assist in positioning the replacement VD was adjusted for proper fit-up. The upper adjustable section of the member was extended with the use of an air tugger on the platform connected to a padeye on the upper section.

The lower end of the replacement VD was wet welded with a 3/4" fillet weld. Due to the buckle at the lower node in the original VD member, the member had to be removed leaving only a 6 in. stub at this end. This did not leave sufficient length for slot welding the replacement VD for the required weld length. The solution from Global was to install a "Shear Pup" along the topside of the member at the intersection with the leg joint can. For this repair, the "Shear Pup" consisted of a 24" OD x 0.500" pipe cut lengthwise to include approximately 220 degrees of pipe and coped to fit the 40" OD leg joint can with a cap plate on the other end. The "Shear Pup" weld preparation was similar to the replacement VD with the pipe end internally beveled to fit the 40" OD joint can. This was wet welded with a 3/4" fillet weld to the leg joint can and the 24" OD replacement VD to complete this end connection. The upper member end section was dry welded with a full penetration groove weld to the 40" OD leg joint can. The upper free end of the 26" OD slip-sleeve was then dry welded with a 3/4" fillet weld to complete this VD repair.

South Timbalier 151 J

The South Timbalier 151 J platform is an eight pile platform installed in 1962 in 139 feet of water. This platform is a drilling and production well satellite platform in the ST 151 field. This platform was severely damaged. The repaired damage on this structure consisted of a total of four buckled and one separated vertical diagonal members, four of these damaged members being in the bottom framing bay between (-)139 and (-)102 feet with the remaining damaged member being one bay upward between (-)102 to (-)62 feet. All of the four buckled 16" OD x 0.406" VD members exhibited a similar failure scenario. These failures consist of a major local buckle failure in the center of the member accompanied by a transverse crack in the buckle with the lower VD member end typically buckled 6 to 18 in. from the connecting leg joint can. The remaining damaged VD member consisted of a tension failure in the lower end of the member at the joint can, with the member tearing free and propagating a crack into the joint can. Figure 6 illustrates these repairs.

The required repairs for the damage at this platform were extensive but straight forward. Each of the damaged 16" OD x 0.406" VD members were required to be replaced with a 16" OD x 0.500" replacement VD member. The proposed repair method by Oceaneering was to remove the existing damaged VD member by cutting and arc gouging, then to prepare the joint can to accept the replacement VD member by grinding the surface smooth. The replacement VD members consisted of an adjustable 16" OD x 0.500" replacement VD member fitted with an 18" OD x 0.938" slip-sleeve for installation with 3/4" x 24" OD x 33 1/2" ID rolled doubler plates on the member ends to fit the connecting leg joint cans. Each replacement VD then was fit up into position using the structure crane or air tuggers. The members were placed and extended into position using attached padeyes to secure the member. The member ends and doubler plates were checked for proper fitup and wet welded with 3/4" fillet welds to the leg joint cans. The slip-sleeve connection was then wet welded with a 3/8" fillet weld to complete the repair. The tension VD member failure was similarly repaired with the exception that the cracked and torn leg area was cut and ground smooth and the rolled doubler plate was enlarged sufficiently to cover the affected area to complete the repairs for this platform.

South Timbalier 135 M

The South Timbalier 135 M platform is a six-pile platform installed in 1966 in a water depth of 116 feet. This platform is a satellite well production platform supporting 5 wells in the ST 135 field. The repaired damage on this platform consisted of a horizontal X-brace joint which had a large 12" wide x 24" long hole torn from the through member when a secondary vertical bracing member was torn free. The 16" OD x 0.408" horizontal X-brace members in Plane B at (-)9 feet were braced in the vertical direction with a 12.750" OD x 0.375" vertical members running from the top and bottom of this joint to the Plane A at and C horizontal X-brace framing respectively. The vertical bracing member from Plane B at (-9) feet to Plane A at (+)21 feet had severely corroded at the waterline and was scheduled to be removed as being unnecessary. This member apparently failed at the waterline and subsequently tore the attached X-brace at Plane B. Figure 7 illustrates this repair.

Repair of the X-brace framing was complicated by the attached conductor guide framing at and around this joint. Three 8.625" x 0.322" OD conductor guide braces frame horizontally into this X-brace joint with the 12.750" OD vertical brace framing into the bottom of the joint. Replacement of the X-brace joint was considered and quickly abandoned due to the complex framing. The repair consisted of installing an 18" OD x 0.938 doubler covering the top quarter of the 16" OD member circumference. The framing member at the joint was cut away sufficiently to place the 8 feet long doubler along the length of the through member. This was wet welded with 3/8" fillet welds. Two 4 feet long doublers coped at one end for the installed 18" OD doubler was fitted to the 16" OD framing members. These doublers were likewise wet welded with 3/8" fillet welds to complete this repair.

SUMMARY

The 1992 post-Hurricane Andrew underwater inspection program and the resulting 1993 repair program provided an unique opportunity to learn and experience a wide variety of underwater platform repairs. From this underwater repair program, interesting repair techniques were experienced and current repair limitations were discovered.

The primary issue encountered in designing the weldments and performing the underwater welding was obtaining sufficient weld area or weld length to meet the strength requirements for the repair. With limitations on wet weld types allowed, a primary concern in designing an underwater wet weld repair is the size of the required weld. The optimum weld size for a fillet type weld was found to be with a 1/2" leg. With welds larger than 1/2", the additional weld metal provides a diminishing increase in shear area for the weld and thus weld strength. These larger welds are therefore less cost effective to use in repair work. In designing repair weldments however, the available welding area is often the critical factor to be considered.

One innovative concept used in this repair program to overcome this restriction is the "Shear Pup" as used at ST 134 W platform. The "Shear Pup" offers many advantages over alternative strengthening techniques. This concept offers the benefit of ease of fabrication and field installation. Its compact shape maximizes the added weld length for the space occupied and minimizes restrained weld joint geometry and stress concentrations. Additionally, the welding area is readily accessible on the exterior of the adjoining members.

Where possible, the thickness of doubler plates used should be limited to 1/2" in thickness. The ability to field adjust the curvature of a doubler plate during installation is severely limited with doubler plates thicker than 1/2". The thickness of doubler plates used in member end connection repairs are generally required to be greater than 1/2" to resist punching shear and plate bending.

When internally beveling a replacement VD member to butt fit a leg member over a removed member stub, caution should be exercised in that the pipe is beveled only for fitting to the existing leg member and not include the existing member stub weld profile. Excess existing weld fillet should be ground off before installation of the replacement VD member.

During the course of this repair program, many hours were spent designing the repairs and the action plan in order to accomplish these repairs. The full cooperation exhibited by both Global Divers and Contractors, Inc. and Oceaneering International Inc. greatly assisted in the successful and timely completion of this project.

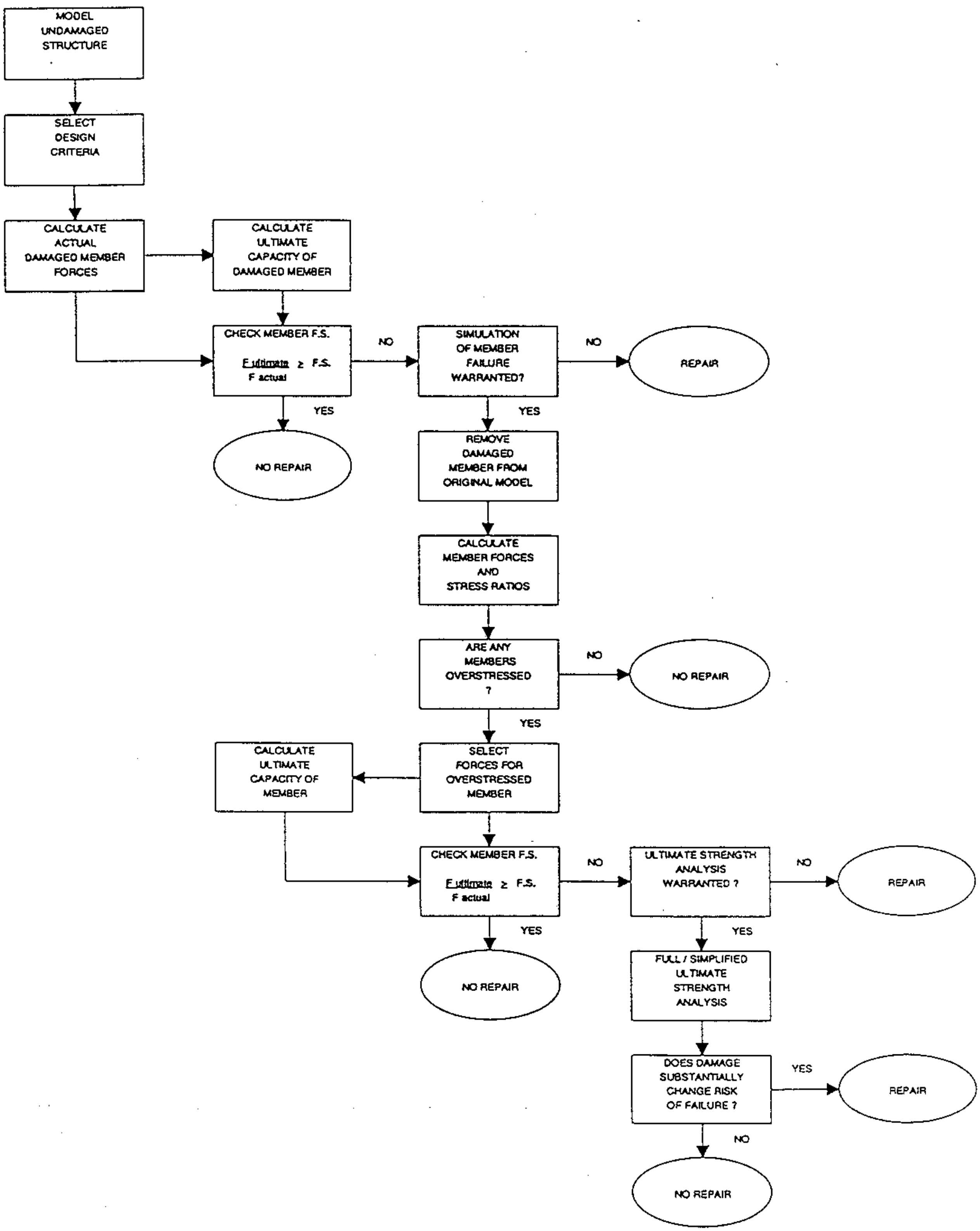


Figure 1 - Decision Making Procedure for Repair of Underwater Damage

Platform	Contractor	Water Depth	Description
EI 231 CB	Global	-62	Repair crack in Vertical Diagonal member -62' to -27' at LEG stiffener. Arc gouge crack and wet weld stiffener and crack. MPI wet weld repairs for any relevant indications.
SS 169 A	Global	-52	Repair 60" long crack in LEG around Vertical Diagonal member -51' to -31' at joint node. Arc gouge and wet weld crack. Install plate doubler with replacement Vertical Diagonal member. MPI wet weld repairs for any relevant indications.
ST 21 E	Global	-36	Replace separated Vertical Diagonal member -36' to -14' with replacement Vertical Diagonal member. MPI wet weld repairs for any relevant indications.
ST 134 W	Global	-31	Replace buckled Vertical Diagonal -31' to +13' with replacement Vertical Diagonal member. MPI wet weld repairs for any relevant indications.
ST 135 M	Global	-15	Repair hole in Horizontal X-brace joint at -15'. Trim, gouge and grind hole and intersecting members to install pipe doublers over members. MPI wet weld repairs for any relevant indications.
ST 151 Prod 1	Global	-26	Replace buckled Vertical X-brace -26 to +14' with replacement Vertical Diagonal member. MPI wet weld repairs for any relevant indications.
	Global	-26	Repair crack in Vertical X-brace at joint -8'. Arrest crack by drilling and install angle section as joint reinforcement. MPI wet weld repairs for any relevant indications.
	Global	-26	Repair crack indication at Vertical K-joint -26' by grinding. MPI wet weld repairs for any relevant indications.
ST 151 L	Global	-26	Replace dented and cracked Vertical X-brace with Vertical Diagonal member. MPI wet weld repairs for any relevant indications.
ST 188 CA	Global	-35	Repair cracked Horizontal and conductor guide brace with full encirclement pipe doubler. MPI wet weld repairs for any relevant indications.
ST 151 J	Oceaneering	-102	Replace buckled B2-C2 Vertical Diagonal member -102 to -64 with replacement Vertical Diagoonal member. MPI wet weld repairs for any relevant indications.
	Oceaneering	-140	Replace buckled C2-D2 Vertical Diagonal member -140 to -102 with replacement Vertical Diagonal member. MPI wet weld repairs for any relevant indications.
	Oceaneering	-140	Replace buckled B1-C1 Vertical Diagonal member -140 to -102 with replacement Vertical Diagonal member. MPI wet weld repairs for any relevant indications.
	Oceaneering	-140	Replace buckled A2-B2 Vertical Diagonal member -140 to -102 with replacement Vertical Diagonal member. MPI wet weld repairs for any relevant indications.
	Oceaneering	-140	Replace separated B1-A1 Vertical Diagonal member -140 to -102 with replacement Vertical Diagonal member with doubler plate. MPI wet weld repairs for any relevant indications.

Figure 2 - Summary of 1993 Underwater Repairs

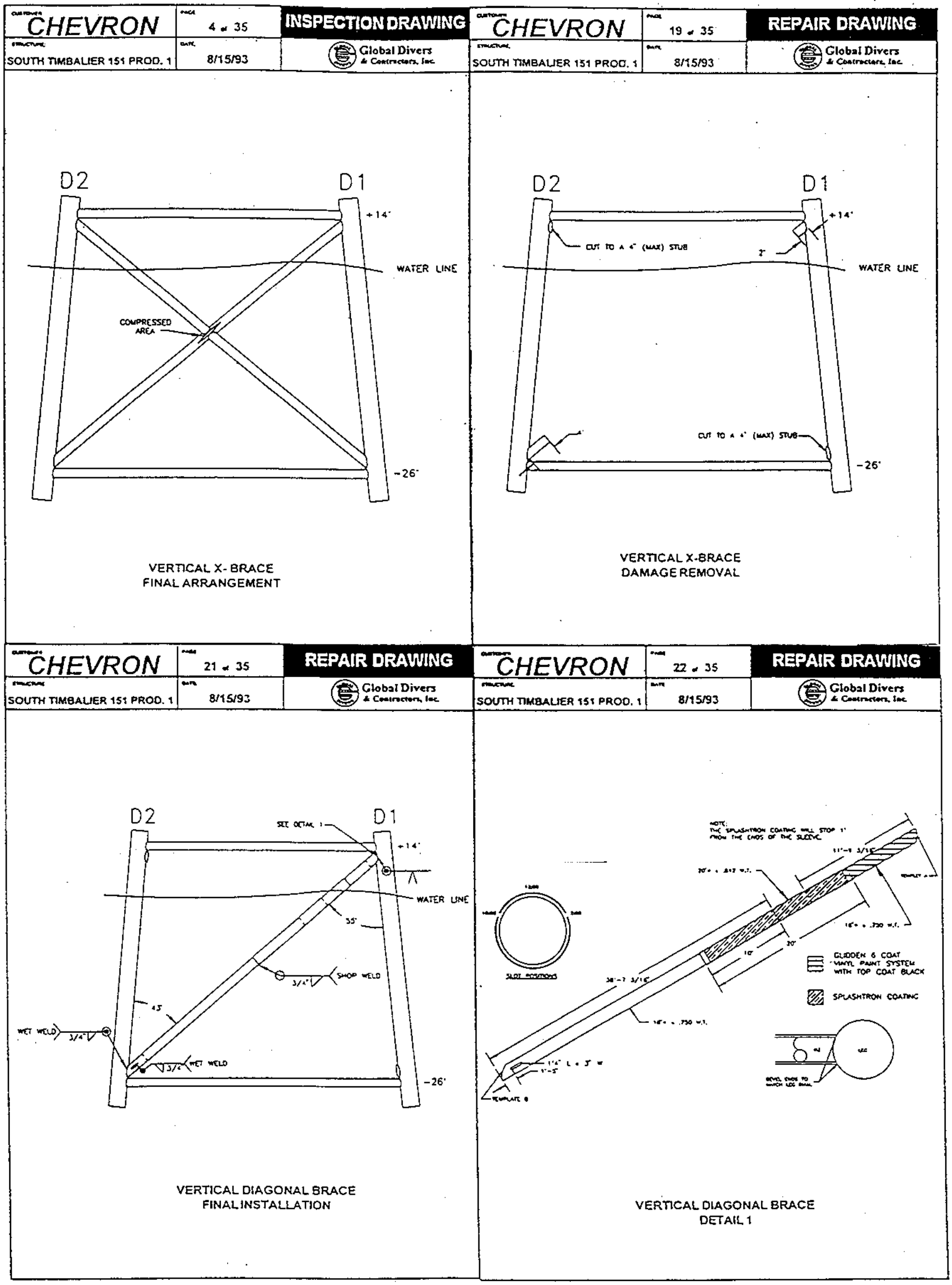
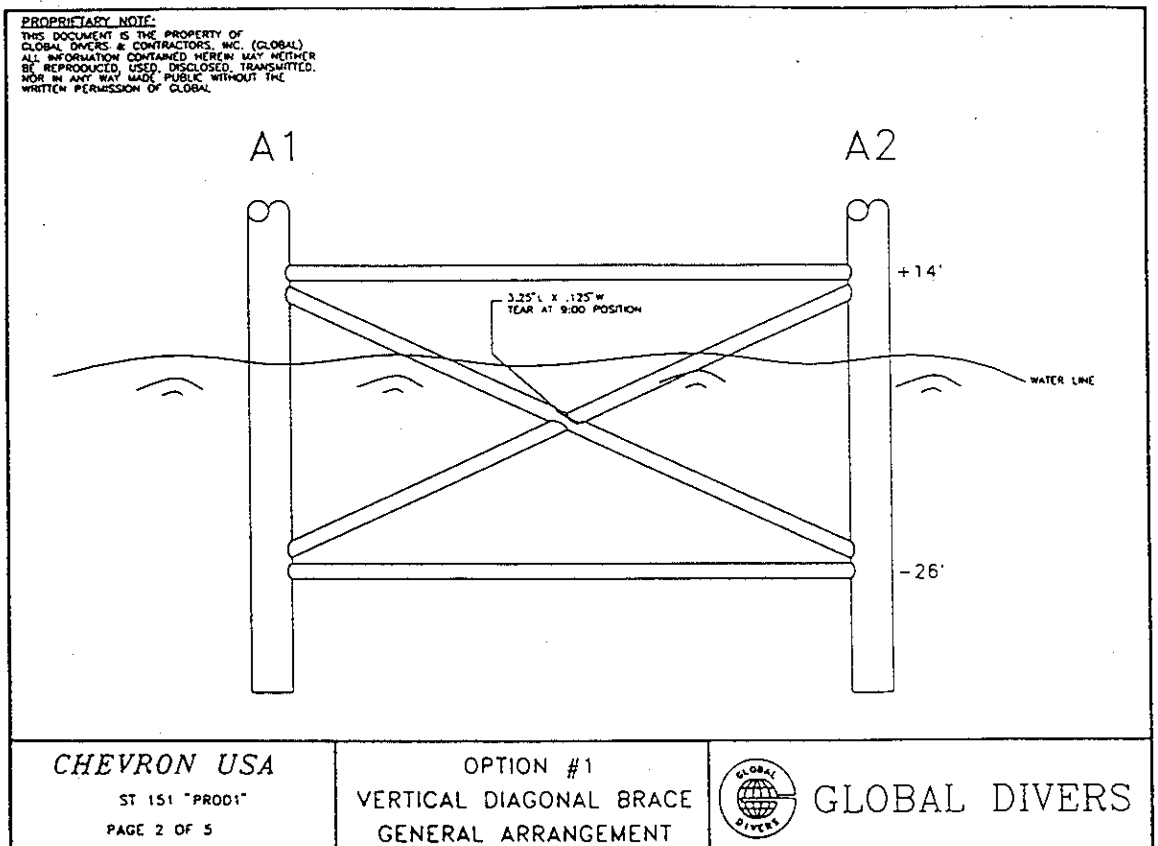


Figure 3 - South Timbalier 151 Production 1 Platform Repair



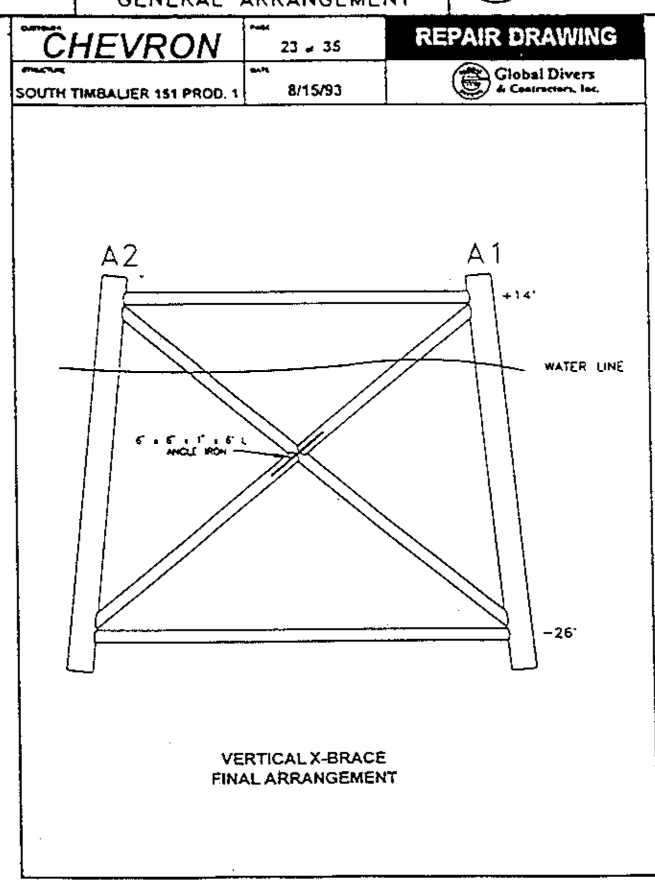


Figure 4 - South Timbalier 151 Production 1 Platform Repair

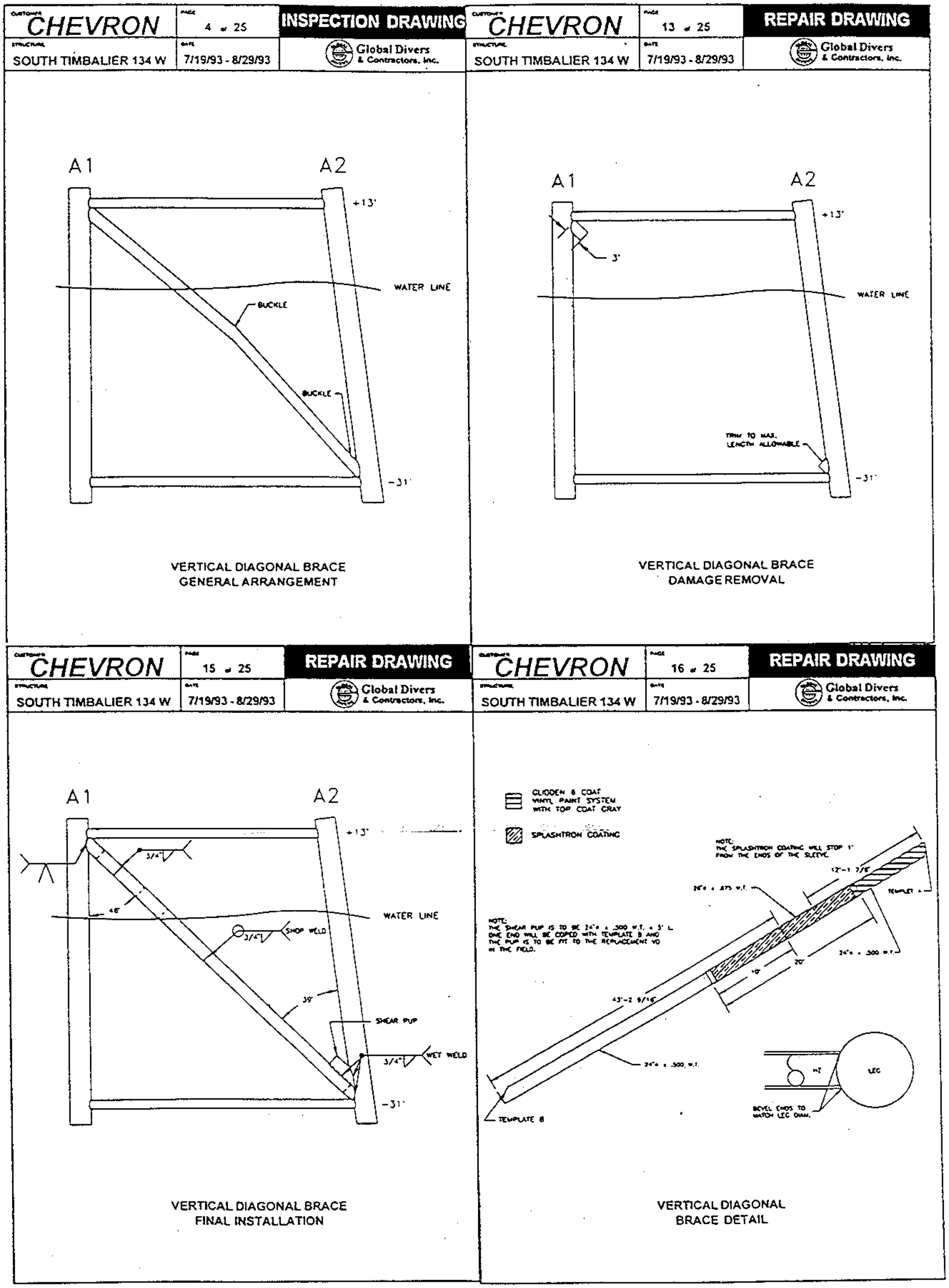


Figure 5 - South Timbalier 134 W Platform Repair

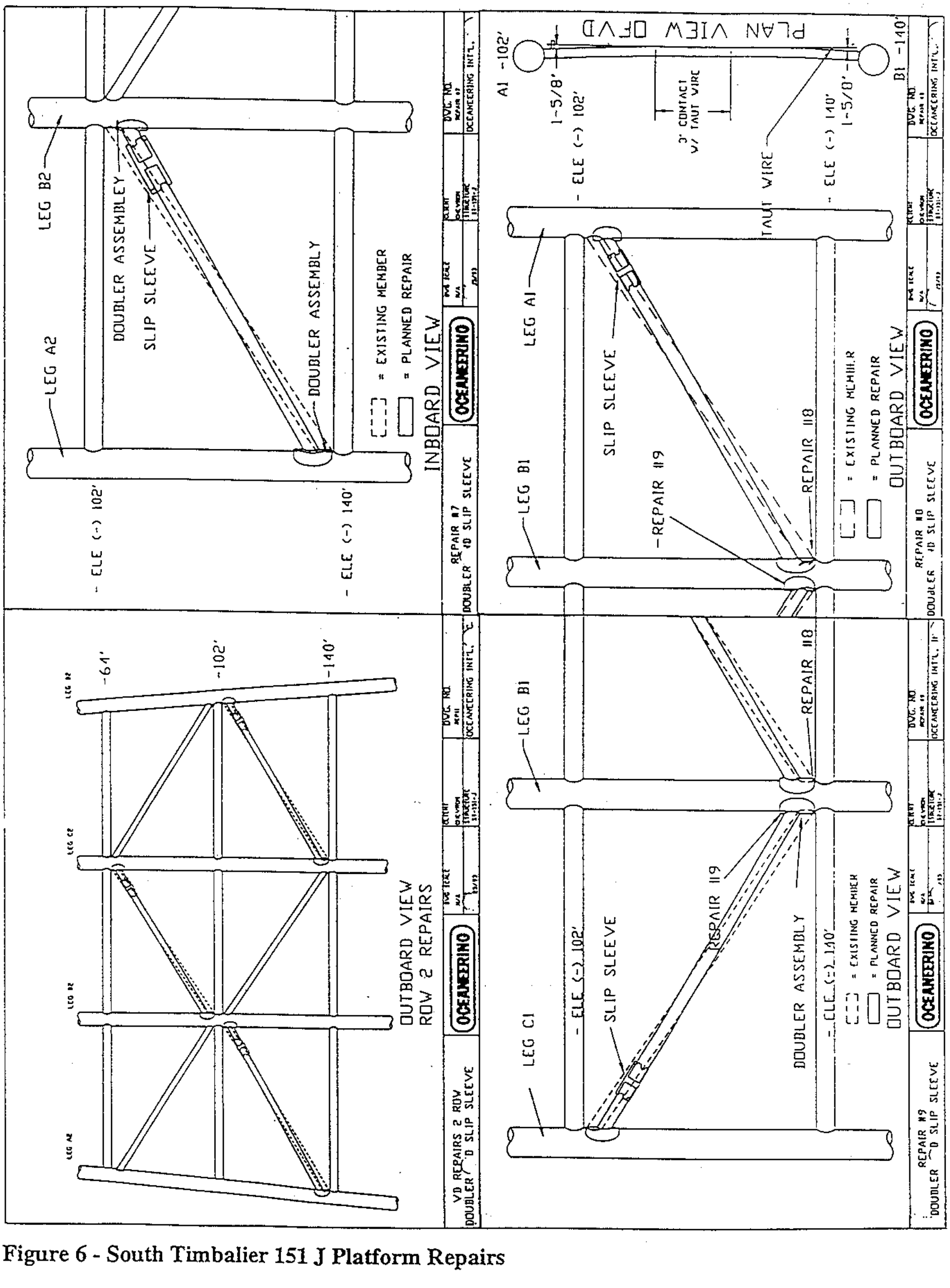


Figure 6 - South Timbalier 151 J Platform Repairs

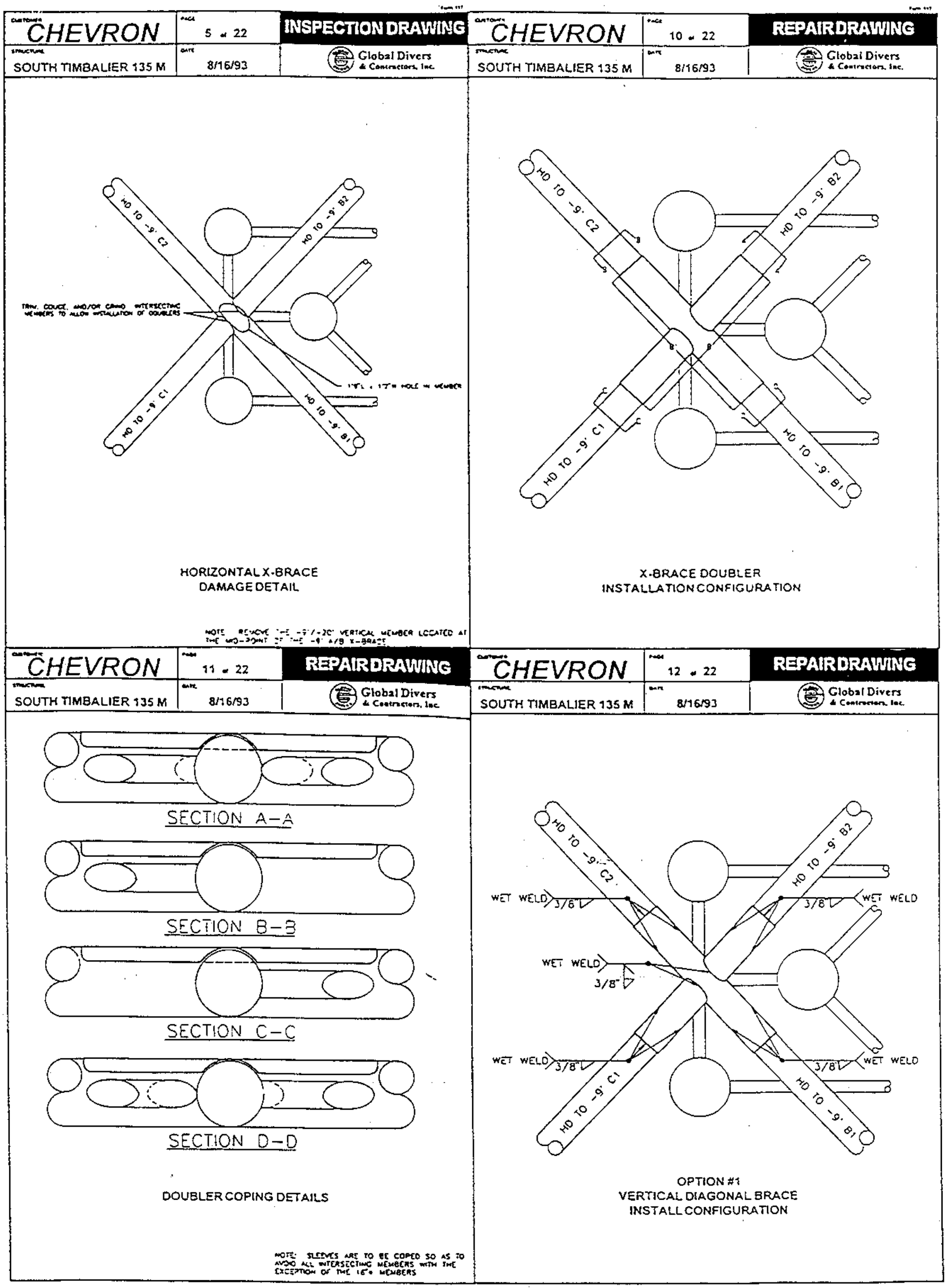


Figure 7 - South Timbalier 135 M Platform Repair

HURRICANE "ANDREW" DAMAGED PLATFORM REPAIRED BY WET WELDING

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Abstract

Trunkline Gas Company's (a business unit of Panhandle Eastern Corporation) T-23 platform located in South Timbalier Block 52 was repaired by wet welding after sustaining structural damage caused by Hurricane Andrew. The successful replacement of two critical K-brace nodes, at the -38 to -58 feet water depth, by underwater wet welding provided a significant cost savings, minimized the offshore exposure time and returned the platform to its original structural integrity without shutting down the transmission of natural gas.

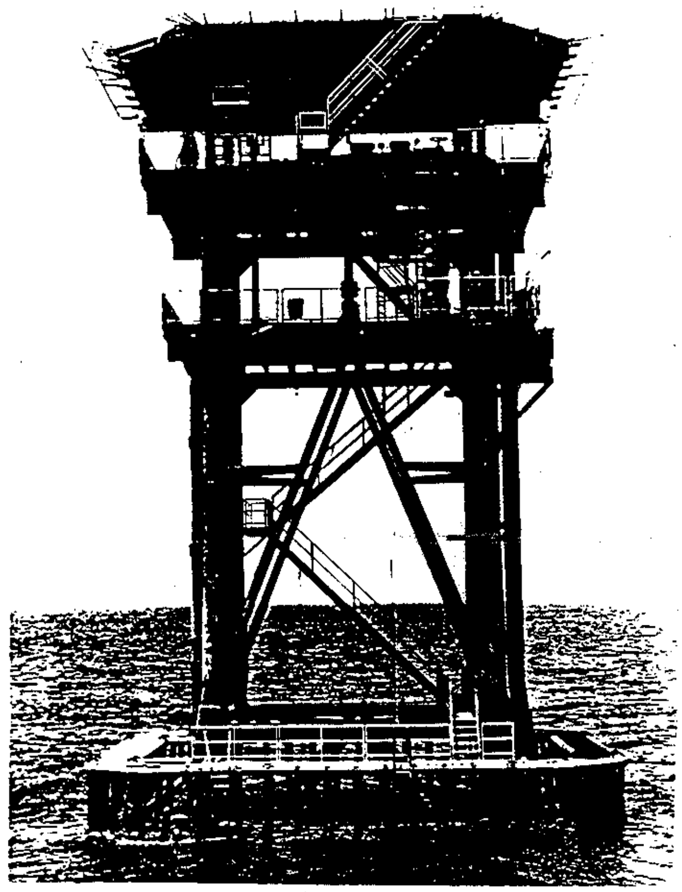

Figure 1. The T-23 Structure

Hurricane Andrew

In August 1992 a highly destructive hurricane began its path across South Florida and into the Gulf of Mexico crashing into the Louisiana Coast Line. Weather reports indicated that Hurricane Andrew had wind velocities of 165 mph causing waves to reach as high as 70 feet. Several offshore platforms in the Gulf of Mexico experienced damage. Platform damage varied from localized cracks in members to structures completely toppled by the force of the storm.

Post Storm Inspection

The South Timbalier 52 structure (Figure 1) was inspected on September 6, 1992 immediately after the passage of Hurricane Andrew (August 20 - 21, 1992). The structure is used as a gathering site for the natural gas reserves of the Terrebonne System. Two underwater midpoint nodes (-39' MP Horizontal A1-B1 and -39' MP Horizontal A2-B2) were found to have visual indications of punching shear type failures at the vertical diagonal attachments and the 18 inch diameter horizontal chord members were deformed. Refer to Figure 2 and 3. Several other areas indicated that large strain had occurred due to missing marine growth at member intersections. No other relevant damage was observed on the structure.

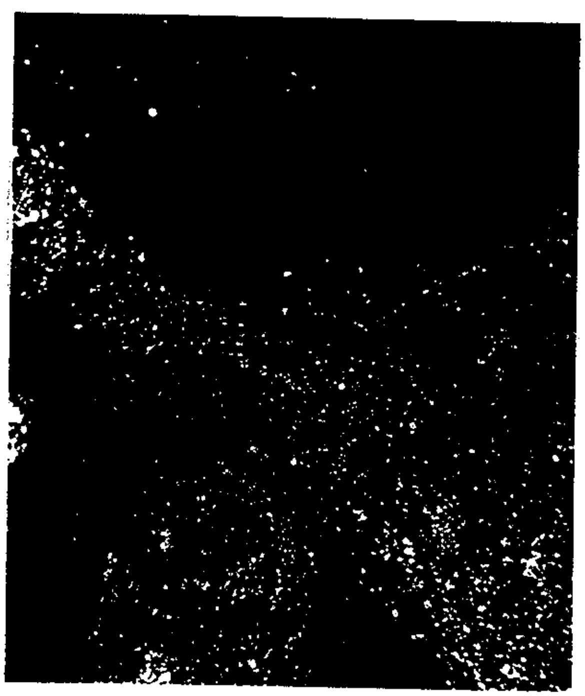

Figure 2 - Damaged Node

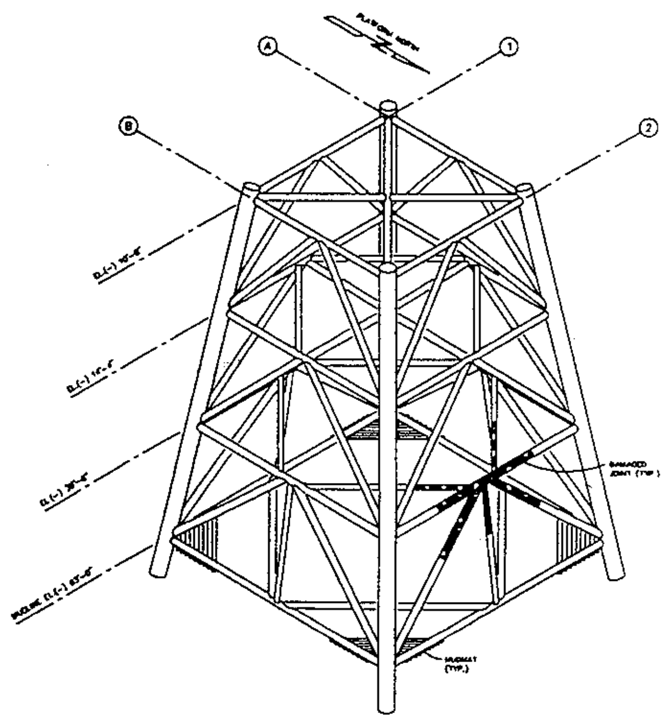

Figure 3
Isometric View of T-23 Structure

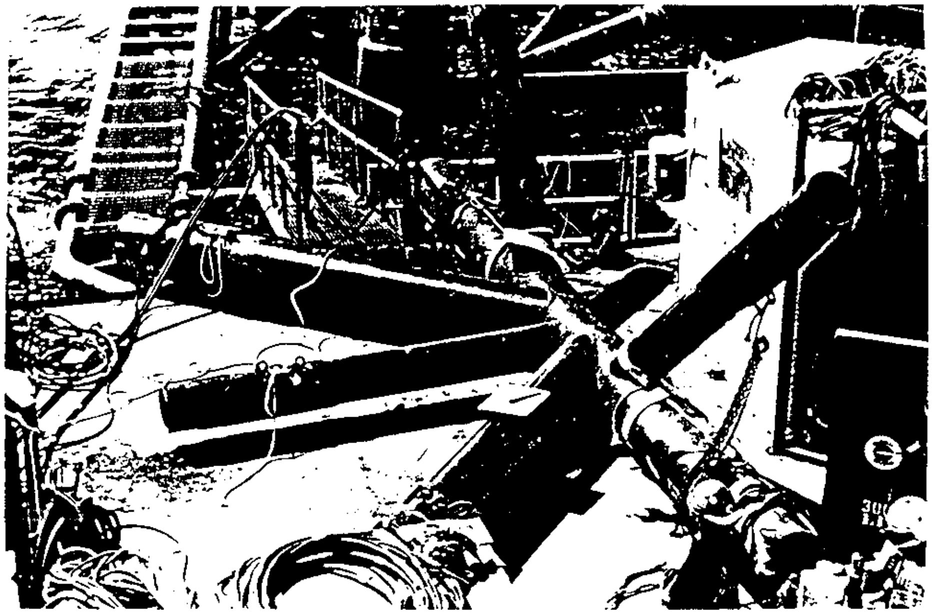

Figure 4 Replacement Nodes

Engineering the Repair

The damaged nodes were redesigned using API RP 2A (19th Edition) requirements regarding strength requirements and punching shear and the wet welded design concept.

As a result of the design process, the wall thickness of the 18 inch diameter, -39' horizontal chord members were increased from 0.375 inches to 0.938 inches. Scalloped sliding sleeves were designed (and fillet welds sized) to connect the new node assemblies to the existing members. The fillet welds were sized based on the maximum API allowable load carrying capacity of the existing members connecting to the respective damaged joints. This calculated load was far greater than the design load for those members resulting from the 25 year return interval hurricane.

Wet Welding Procedure

In order to determine the feasibility of the repair procedure and proper wet welding procedure to utilize (multiple temper bead technique or conventional multipass technique), the carbon equivalent (CE) of the node members needed to be determined.

On December 4, 1992, base metal samples (2 inches in diameter) were removed from each member (and from both nodes) by oxy-arc cutting. A chemical analysis was made on each of these samples such that the carbon equivalent (CE) could be determined using the International Institute of Welding (IIW) formula:

$$CE = C + Mn/6 + (Cr+Mo+V)/5 + (Ni+Cu)/15$$

The CE was determined by chemical analysis and the results ranged from 0.31 to 0.42 (See Table 1). The CE exceeded 0.40 (the accepted maximum limit for utilizing a conventional multipass wet welding technique).

Due to the obvious high cooling rates encountered in wet welding, and that high CE carbon steels pose a greater risk of cracking, the wet multiple temper bead (MTB) technique was chosen due to its success as previously reported by others[1,2]. An additional benefit with choosing the MTB technique would be that the technique would further refine the HAZ and weld metal grain structure, thus reducing hardness and provide additional toughness.

TABLE 1 - CARBON EQUIVALENT RESULTS

	1	2	3	4	5	6	7	8	9	10	11	12	13	14
ϕ	18"	18"	18"	12.75	18"	12.75	12.75	18"	18"	18"	12.75	18"	12.75	12.75
	H	H	VD	V	VD	HD	HD	H	H	VD	V	VD	HD	HD
W.T	.360	.356	.506	.335	.499	.335	.340	.366	.358	.498	.325	.511	.325	.343
C	0.23	0.24	0.23	0.26	0.27	0.23	0.25	0.22	0.24	0.23	0.20	0.21	0.21	0.23
Mn	0.43	0.70	0.86	0.65	0.85	0.78	0.74	0.69	0.69	0.67	0.65	0.87	0.72	0.73
P	0.002	0.004	0.005	0.004	0.011	0.006	0.008	0.005	0.005	0.003	0.005	0.005	0.007	0.006
S	0.016	0.021	0.016	0.026	0.013	0.012	0.022	0.015	0.017	0.013	0.011	0.020	0.020	0.011
Si	0.03	0.05	0.05	0.07	0.02	0.07	0.06	0.02	0.02	0.15	0.05	0.05	0.06	0.07
Ni	0.01	0.02	0.01	0.03	0.02	0.02	0.04	0.01	0.01	0.02	0.02	0.01	0.03	0.02
Cr	0.02	0.04	0.04	0.08	0.02	0.08	0.08	0.05	0.05	0.04	0.08	0.04	0.08	0.08
Mo	0.01	0.02	0.01	0.02	0.01	0.02	0.02	0.02	0.02	0.01	0.02	0.01	0.02	0.02
Cu	0.03	0.02	0.02	0.03	0.06	0.02	0.04	0.02	0.02	0.07	0.03	0.02	0.04	0.03
CE	0.31	0.37	0.39	0.39	0.423	0.37	0:40	0.35	0.37	0.36	0.33	0.37	0.35	0.38

Legend: H = Horizontal, HD = Horizontal Diagonal, V = Vertical, VD = Vertical Diagonal
Note: Vanadium content was <0.001 for all samples.

Supplemental Requirements

Additionally, supplemental Charpy V-notch impact specimens (See Table 2 - the average of five (5) charpy specimens is presented), two (2) all weld metal tensile specimens (See Table 3), and two fillet weld shear tests (See Table 4) and a hardness traverse (See Table 5) were prepared.

The minimum acceptance criteria for impacts strength was 20 ft.-lbs. at 32 degrees F. Base metal (longitudinal and transverse), weld metal, and heat affected zone (HAZ) impact specimens were prepared from the procedure weldments and tested.

Test Results

As a result of the temper bead technique and heat input control, charpy V-Notch impact tests were completed on the base metal, weld metal and HAZ. Five charpy samples per set were tested at 32°F and all individual values were above 30 ft-lbs. A macro cross-section was prepared for vickers hardness testing. The overall average in the coarse grain HAZ was 295.5 with one value at 417 vickers. This isolated measurement was due to improper placement of the temper bead.

TABLE 2 - CHARPY IMPACT TEST

Notch Location	Sample Size	Test Temp	Avg. Energy (Ft-Lbs)	Percent Shear	Mils Exp
HAZ - Long	10mm x 10mm	+32 F	39	55	36
Weld Metal	10mm x 10mm	+32 F	32	100	39
Base - Long	10mm x 10mm	+32 F	58	70	55
Base - Trans	10mm x 10mm	+32 F	34	65	39

Legend: Long = Longitudinal   Trans = Transverse

The two fillet weld shear specimens had an average shear strength of 51,000 PSI. The AWS D3.6-93 "Specification for Underwater Welding"[3] requires a minimum shear strength of 60% of the specified tensile strength of the base metal (60,000 PSI) for Class B welds. A Class A weld is required to equal 60% of the tensile strength of the filler metal as measured in an all-weld-metal tensile test. The two all-weld-metal tensile test results had an average strength of 70,750 PSI and 60% of that average is 42,450 PSI. It is clear to see that the results of the Charpy Impact tests, the fillet weld shear tests and the all-weld-metal tensile tests, exceed the requirements of Class A welds.

TABLE 3 - ALL WELD METAL TENSILE TESTS

Sample I.D	Dia In.	Area $In.^2$	Ultimate Load Lbs.	Load @ Yield Lbs.	Tensile PSI	Yield PSI	Elong %	Red of Area %
WM 1	.500	.196	13,200	11,650	67,500	59,500	12	19
WM 2	.504	.200	14,750	12,850	74,000	64,000	15	24

Weld: 0.2% Strain Offset   2" Gage Length

16 inch diameter girth weld (with backing) was made at 33 FSW for further supplemental testing. The radiograph was evaluated to the acceptance criteria of AWS D3.6 -93 and API 1104. The radiograph was satisfactory to AWS D3.6 but due to the quantity (salt and pepper type) of porosity, it did not meet the acceptance criteria of API 1104.

TABLE 4 - Fillet Weld Shear Results

Specimen No.	Dimensions		Area Sq. In.	Ultimate Load	Ultimate Stress PSI
	Width	Thickness			
1	5.595"	0.257"	1.438	74,058 Lb	51,500
2	5.567"	0.244"	1.358	68,870 Lb	50,500

LOCATION					ID	HARDNESS	LOCATION					ID	HARDNESS
B1	B2	HAZ1	HAZ2	W	NO	NUMBER	B1	B2	HAZ1	HAZ2	W	NO	NUMBER
X					1	148.8					X	15	242
X					2	147.1					X	16	224
		X			3	345					X	17	210
		X			4	342					X	18	222
		X			5	251					X	19	225
		X			6	235					X	20	235
		X			7	279					X	21	225
		X			8	242					X	22	193
			X		9	289					X	23	206
			X		10	272					X	24	276
			X		11	232					X	25	227
			X		12	249		X				26	143.1
			X		13	394		X				27	141.5
			X		14	417							

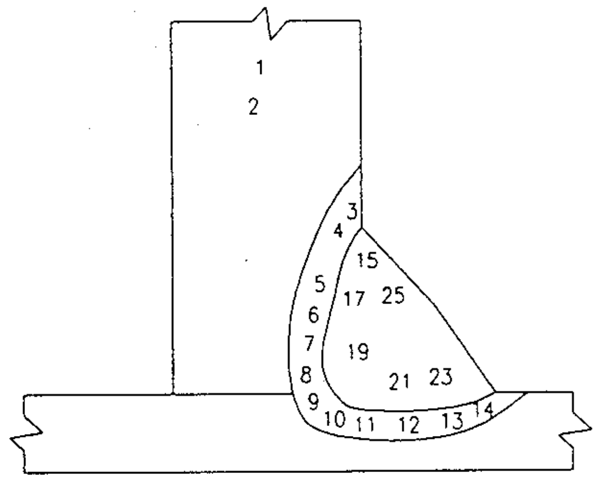

Figure 5 - Vickers 10 Kg. Hardness Transverse

Welder Qualification

All of the welding procedure qualification testing and welder performance qualification testing was completed at Global Divers & Contractors, Inc., Hyperbaric Welding Facility located at their Port of Iberia, Louisiana, Operations Base. Eleven welders divers were then qualified using the qualified welding procedure.

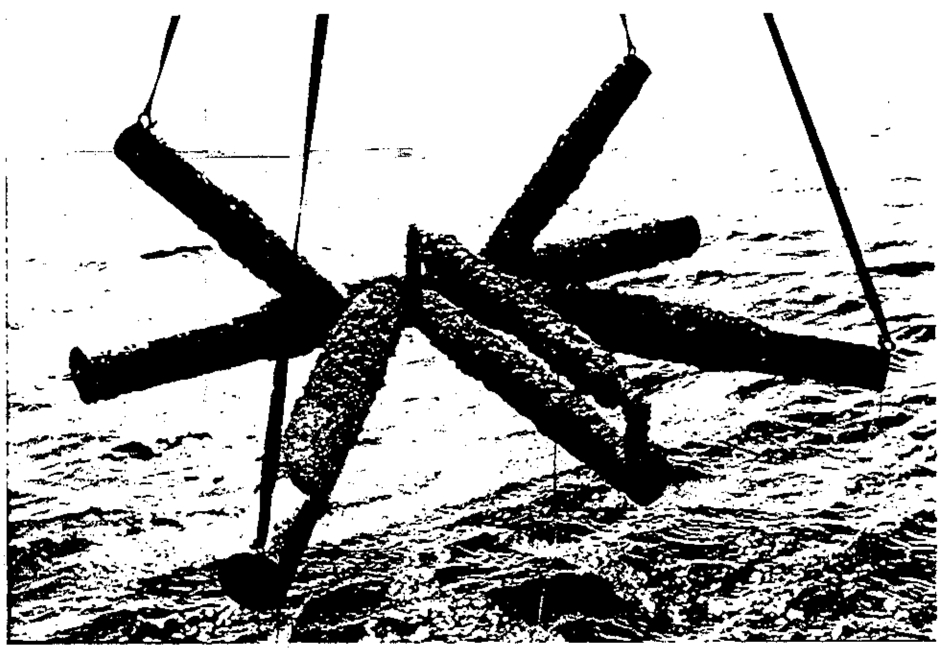

Figure 6 - Damaged Node

Fabrication

Fabrication of the two node assemblies,scal-loped sliding sleeves, and two replacement riser clamps were prepared as shown in Figure 4.

Figure 7 - Sliding Sleeve Fit-up

Installation

On May 19, 1993, the 130 Class Lift Boat mobilized from the Port of Iberia, Louisiana to the South Timbalier 52 (T-23) structure. The South Timbalier 52 structure is a four leg design standing in approximately 68 feet of water. Refer to Figure 3.

The diving support vessel M/V "GD 122", a 122 ft. utility vessel, rendezvoused with the "RAM II" at the T-23 structure, bringing with it the diving construction crew for the project. The "GD 122" was the dedicated supply vessel throughout the project.

The repair project began by removing the two damaged nodes (See Figure 6) and grit blasting the remaining structural members in preparation for welding.

Final dimensions were measured to insure the new nodes would fit,and the new nodes were lowered into place and fit up with a 2" gap between the new and existing members. The capsulated sleeves were slid over the existing members and centered over the 2" gap(See Figure 7). A tack weld was used to hold

Figure 8 - Completed Wet Weld

the sleeve inplace, while the wet welding commenced.

The project was completed in 21 days. Fourteen capsulated sleeves (eight with 20" O.D. and six 14" O.D.) were welded on both sides. The fillet weld size was 1/2" on the 12 3/4 O.D. members and 3/4" on the 18" members.

All welds were photographed and magnetic particle inspected and no defects were found. See Figure 8.

Summary

The two node assemblies and two riser clamps were installed between May 20 and June 9, 1993. The project, including weather down time, took a total of 21 days. A total of 233 dives were recorded (167 dives were dedicated welding dives). Approximately 595 welding/diving man-hours were spent on this project without any lost time accidents.

The above mentioned accomplishments along with the previous summarized test data indicated that underwater welding repair concepts are a feasible and cost effective solution to offshore platform repair in the Gulf of Mexico.

References

[1]Ibarra, S., Reed, R.L., Smith, J.K., O'Conner, P.E., Grubbs, C.E., Underwater Wet Welding of Higher-Carbon-Equivalent Steels: OTC 6214 pp. 135-142, 22nd OTC, Houston, TX, May 7-10, 1990.

[2]Ibarra, S., Reed, R.L., Smith, J.K. Pachniuk, I., Grubbs, C.E., The Structural Repair of a North Sea Platform Using Underwater Wet Welding Techniques: OTC 6652 pp. 57-66, 23rd OTC, Houston, TX , May 6-9, 1991.

[3]American Welding Society, ANSI/AWS D3.6-93, "Specification for Underwater Welding"

Future Opportunities in Underwater Welding

Friction Welding Techniques

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Friction Stud Welding

Friction stud welding (FSW) is an established technology for which machines are available from a number of commercial suppliers. The primary benefit of this type of welding is that it is an autogenous solid state process that does not require filler metals or melting of the base metal. FSW is a machine tool operated process that does not require welder-trained operators. Remotely-operated vehicles (ROVs) can be used to apply FSW at depths that are far beyond the limits of diver support. The process employs very short weld times, is energy efficient, and has excellent reproducibility. It does not require a hyperbaric habitat, and uses a simple plastic foam shroud to shield the process zone from the environment. FSW is currently used to electrically couple sacrificial anodes to steel structures, and also has applications in the attachment of shear keys for grouted clamp repairs, salvage, pipeline repair, and hot tapping.

Friction Taper Stitch Welding

Friction taper stitch welding (FSTW) is an emerging technology under development for real crack repair applications. FSTW is essentially a development of the established FSW process, and is envisioned primarily as a low-cost alternative to manual grading and rewelding. It eliminates the need for skilled pre-weld gouging and manual arc welding. FSTW can be used to repair cracked regions by using overlapping tapered plugs that are friction-welded in tapered drilled holes. The process has a very rapid weld cycle, and a single machine with a spindle can interface with drilling, welding, and machining packages. The process is very controllable, and can be used with an ROV or robot arm. Full-thickness repairs of root defects or corrosion/fatigue cracks can be made even if access is limited to one side. The current plate-thickness repair limit of 30 mm (C-Mn steel) is dictated by machine power requirements

Friction Hydro Pillar Processing

Friction Hydro Pillar processing (FHPP) is an experimental low-cost crack repair method that eliminates the need for a hyperbaric habitat. The technique is especially suitable for through-thickness repairs in locations where no backing plate can be applied (i.e., in pipelines). FSTW has been used to join plates by one-sided riveting (i.e., grouted clamp brackets) and for repairs of lamellar cracks. The process is suitable for remote operation. FSTW operates by forcing a rotating consumable rod into parallel holes that have been drilled through a crack. The consumable rod tip is plasticized by the frictional heat, and hydrostatic forces allow welding to occur. Holes measuring 21 mm dia. by 50 mm depth can be filled in 10 seconds, and a series of overlapping welds can be produced to repair a crack. FSTW may be able to repair cracks in thicker plates when the process becomes more fully developed

Radial Friction Welding

Radial Friction Welding (RFW) is a one-shot offshore welding process for rapid joining of pipelines. The economic and technological benefits of the process are apparent from the fact that 219 mm OD by 12.7 mm wall thickness pipe section can be welded in 10 seconds. It can be used to join C-Mn steel, corrosion resistant alloys, and combinations of dissimilar metals. RFW is a machine-tool oriented process, and exhibits excellent reproducibility and high weld integrity. Operators need not be welder-trained. The process has an underwater weld repair capability by replacement of entire sections of damaged underwater pipe.

HOMOPOLAR PIPELINE WELDING, AN OVERVIEW

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ABSTRACT

Homopolar pulse welding (HPW) has been proposed as a one-shot, single stage welding process for the joining of pipe in the J-lay configuration. A joint industries program (JIP) has been formed to develop this process for off-shore, deep water application. At this point, no studies have been conducted on the applicability of the method for underwater service, but its speed and lack of pressure sensitivity makes it an interesting possibility for future, deep water considerations. Homopolar pulse welding utilizes the high current, low voltage electrical pulse produced by a homopolar generator to rapidly resistance heat the interface between abutting pipe ends, producing a full circumference resistance forge weld requiring no filler metal in only three seconds. This five year program began in February 1993, funded by a consortium of six oil companies (Shell, Exxon, BP, Texaco, Amoco, and Mobile). The program's ultimate goal is to produce a prototype system suitable for installation on a barge. The goals for the first two years of the program include demonstrating suitability of the process by producing and evaluating welds in different grades and wall thicknesses of three inch nominal diameter API 5L line pipe. Funding for each year of the program is contingent upon meeting program goals for the previous year.

HOMOPOLAR PULSE WELDING

Process Description

Homopolar pulse welding is properly classified as a resistance-forge welding process. The primary components of an HPW system are the homopolar generator (HPG) and the hydraulic welding fixture. The generator's electrical output circuit terminates in a set of electrodes that surround and connect to the pipes being welded in the fixture.

The pipe ends are machined square and butted with an initial contact pressure. This pressure is a process parameter and influences the electrical resistance at the interface. The two sets of electrodes encircling the pipes are located a fixed distance from the pipe ends and the distance between the electrodes is referred to as the electrode gap. This gap length is also a process parameter and determines the volume of pipe being heated, as well as the rate of post weld heat withdrawal (cooling rate) through the massive copper electrodes. Figure 1 presents a schematic of the HPW process.

The HPW process begins by accelerating the homopolar generator's rotor to a predetermined discharge speed. The generator is discharged by exciting the field and engaging the shielding electric contacts, or brushes, onto the slip ring of the spinning rotor. The resultant current pulse is conducted through the pipes where contact resistance results in extensive localalized heating at the interface. After a preset time delay, upset pressure is applied to the pipes, displacing some metal at the former interface and producing a full circumferential butt weld. The generator discharge speed and field current, pipe and preparation, upset pressure, time between generator discharge, application of upset pressure, and duration of the upset pressure are controllable process parameters which affect weld quality.

The method is similar to other resistance welding methods, with the exception that the energy is delivered in the form of a single high current DC pulse. The method is therefore very fast and does not produce the localized skin heating effects present in AC resistance welding methods. Flash Butt Welding can be used on the same pipe diameters that are being targeted for J-lay, but flash butt welding takes from one to two minutes per joint and produces extensive melting and a large heat affected zone (HAZ). Homopolar pulse welding requires from two to three seconds and is considered a solid state welding process.

Postweld Pulse Heat Treating

The same generator and fixturing used to produce a homopolar pulse weld may be utilized to heat treat the weld HAZ. After the weld zone has cooled below the transformation temperature, another HPG pulse may be used to reheat the weld zone. Electrode location and generator parameters can be preselected to control the amount of heating, width of heated zone, and the subsequent cooling rate.

Working Group Reports

FURTHER DEVELOPMENTS ON STANDARDS, SPECIFICATIONS AND CODES FOR UNDERWATER WELDING AND INSPECTION.

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ABSTRACT

The paper describes the present status of underwater welding standards, changes pending in existing documents, and new items required to meet industry needs in the future. It suggests a direction for those committed to improving the state of the art of the five basic methods of underwater welding currently in use today:

1. Welding in a pressure vessel in which the pressure is reduced to approximately one atmosphere, independent of depth. (Dry welding at one atmosphere).
2. Welding at ambient pressure in a large chamber from which water has been displaced in an atmosphere such that the welder/diver does not work in diving equipment. (Dry welding in a habitat).
3. Welding at ambient pressure in a simple open-bottomed, dry chamber that accommodates, as a minimum the head and shoulders of the welder diver in full diving equipment. (Dry chamber welding).
4. Welding at ambient pressure in a small, transparent, gas-filled enclosure with the welder diver outside in the water. (Dry spot welding).
5. Welding at ambient pressure with the welder diver in the water without any mechanical barrier between the water and the welding arc. (Wet welding).

The paper provides principles, methodologies and a long term strategy for developing and maintaining international standards designed for the underwater welding methods described above, as well as related inspection activities.

INTRODUCTION

Underwater welding standards developed by ANSI/AWS, ASME, U.S. Navy, IIW, American Bureau of Shipping, Det Norske Veritas, Bureau Veritas and others have been the result of an accumulation of many years of experience in this field. While there have been significant improvements in the current standards there is still much work to be done to keep up with the new technologies, materials, consumables, applications, advances in processes, inspection, testing and other considerations.

The necessity to establish a common international standard or base document for underwater welding through efficient organization has never been more apparent. No less obvious is the idea that optimal efficiency can be achieved if an international standard is planned, drafted and maintained using a system driven by consensus.

The main problem is to define the principles on which such a system should be based. The logical approach would be to agree upon predetermined general recommendations and criteria such as contained in existing underwater welding standards, and then to define and refine that criteria as required to maintain consistency with the ever changing state-of-the-art.

Standardization work has already begun through the combined and unilateral efforts of a number of organizations including the IIW Select Committee on Underwater Welding (SCUW), the AWS D3b Subcommittee for Underwater Welding, ABS, ASME, the U.S. Navy, the Paton Institute and others. In June of 1990 the AWS D3b Subcommittee met with the IIW-SCUW to revise the D3.6 Specification to meet the requirements for international standards. The result of this effort was the submittal of the D3.6 Specification in 1993 to the International Standards Organization (ISO) for document approval and numbering as an international standard.

This type of collective approach has proved to provide advantages to all who have participated in forming or revising the basic foundations of their respective standards. Although it is not feasible to fully resolve every problem or issue associated with the various applications and methods of underwater welding, an international cooperative program is suggested as the most viable means of developing and maintaining universally accepted standards for underwater welding. The following sections discuss the status of present standards, the issues facing groups tasked with developing, maintaining and revising underwater welding standards and emphasize a cooperative and interactive path to reach common goals and objectives.

1.0 GENERAL ORGANIZATION

The most important feature of any successful underwater welding standard, code, specification or other governing document is the balance of rational interaction among the five key participant groups: "OPERATOR" (Owner Group), "CONTRACTOR" (Diving, Equipment, Supplier Group), "INSPECTION/TESTING" (Laboratory, Institute, 3rd Party Inspection/Certification, etc. Group), "GOVERNMENT" (Regulatory Group) and "RESEARCH" (Education/Training, Academia Group). The distinction between these five groups is not necessarily commercial or administrative but rather a professional one.

Crucial to the success of such an organization is establishing work groups or teams to facilitate delegation of resource to address the major elements of the working document and progression of the document by consensus. Dividing into smaller sub-groups simplify the process of reaching consensus, once in place, guidelines must be communicated to establish how decisions will be made. Further, the importance of keeping the standard "alive" up-dated and current must be addressed through regularly scheduled committee or group meetings with mandatory periodic revision schedules/frequencies incorporated as necessary.

The following attributes are important to each group or teams success:

- Questioning and listening helps to develop team members respect and understanding.
- Using diplomacy protects self esteem.
- Being mutually supportive encourages cooperation.
- Giving credit enhances cooperation.
- Focusing on agreement, rather than on disagreement.
- Handling difficult situations before they become more difficult.
- Reaching "mini" consensus develops the "habit" of reaching consensus.
- Persistence in obtaining consensus.
- Documenting all comments and participant response for action or continued discussion.

Once the sub-groups or teams have completed the tasks assigned, their work can be presented to the other groups and participants for final evaluation and either approval or revision subject to the comments received from all of the participants. Figure 1 illustrates an effective basic consensus standard organization with sub-work groups or teams.

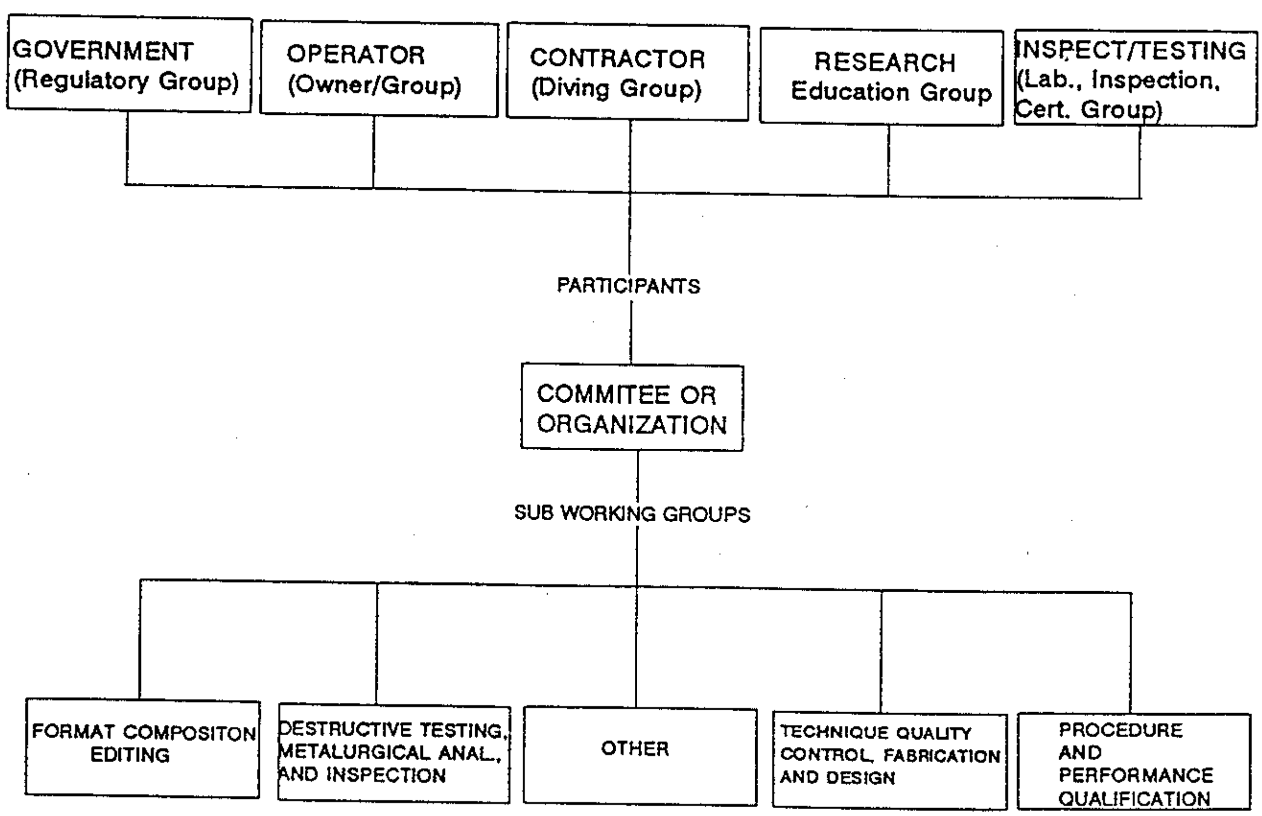

Figure 1 - Effective Consensus Standard Organization Structure

The development and implementation of a successful international standard requires the cooperative efforts of all organizations committed to progressing the state-of-the-art of underwater welding and inspection. This effort may be facilitated by establishing a common platform, such as ISO, from which to work and encouraging participants of one organization to interact and work with other organizations respectively. This approach allows each organization to work independently and still have the advantage of maintaining and revising the base information collectively. In addition, consistency and uniformity throughout the various international standards result in fewer inconsistencies and consequently less confusion experienced by the end user. Figure 2 illustrates a ISO standard support structure made of organizations with common goals and objectives working collectively to draft, maintain and revise a single standard governed by ISO.

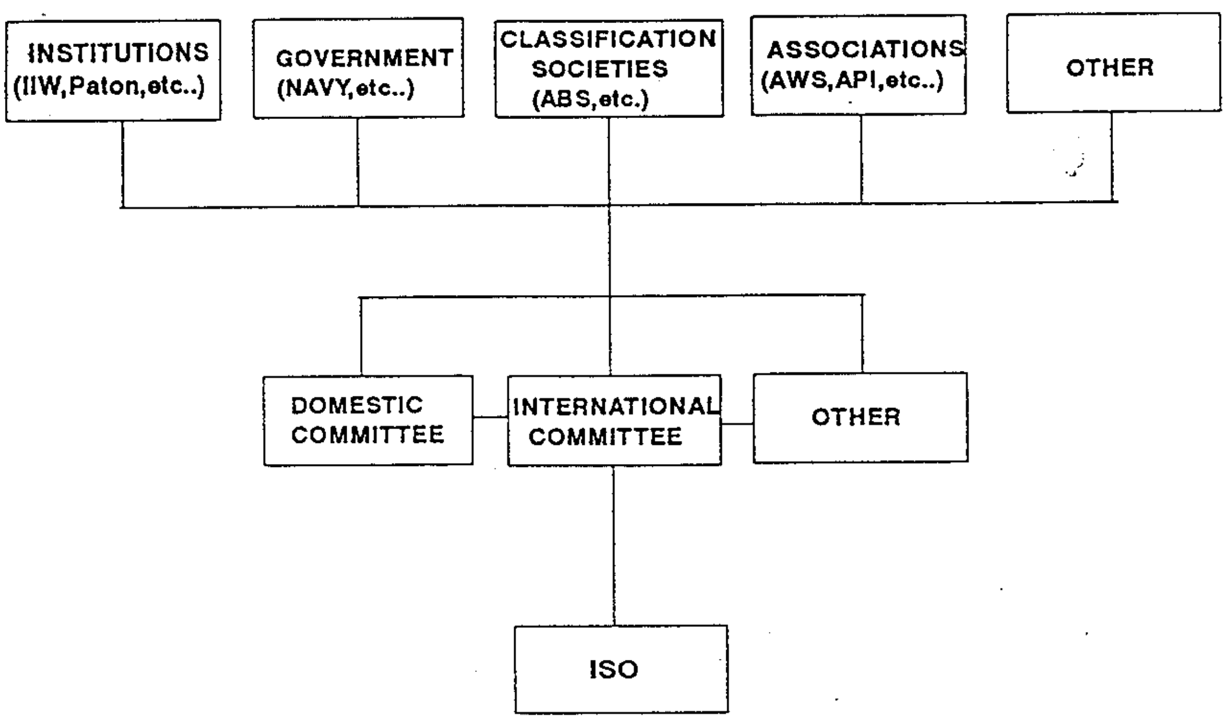

Figure 2 - ISO Standard Support Organization Structure

2.0 KEY ELEMENTS

The key elements of existing underwater welding standards vary in-so-far as format, level of detail, essential and non-essential variables and other considerations. However the following items are generally included for both dry and wet underwater welding:

1. General Provisions
2. Design
3. Workmanship
4. Technique
5. Qualification
6. Inspection, Testing and Quality Assurance

Further developments on Standards, Specifications and Codes are discussed in the following sections relating to the items above.

3.0 GENERAL PROVISIONS

3.1 Scope/Purpose

What should the scope and/or purpose of an underwater welding standard be? This has been a problem since work on the first underwater welding standard was begun. Should dry welding be separated from wet welding or should the two methods be addressed within the same document? Should one document include all weld processes or should there be a separate document for each process? Should design considerations be included or should there be a separate document for design? Should safety and health be within the scope of the standard or is this topic a separate issue?

These and many more problems have faced the participants responsible for drafting underwater welding standards. Presently the scope of most underwater welding standards address both wet and dry underwater welding with a clear distinction between the two. Elements that are not directly a part of the underwater weld procedure or qualification process, such as health and safety, design, etc. are normally referred to another governing document or left up to the customer.

To meet the needs of the user, guidance is needed in a commentary or appendix section on design, safety, health and other related areas of concern as a part of the overall scope of existing underwater welding standards. More important are the need for firm links to be established between organizations who draft and maintain underwater welding standards with organizations responsible for standards related to design, safety and health and other fields. The drafting of new standards, such as, underwater design and safety / health documents, requires the input and output from both organizations respectively to ensure that consistent and predictable results are obtained.

Organizations who draft and maintain underwater welding standards must also strive to resolve differences such as the inconsistencies found between military and industry standards.

3.2 Application

Presently the typical underwater welding standards, with the exception of special interest standards, do not differentiate between various types or applications of underwater welding but rather view this as a customer determination. However in most instances the underwater welding document will take precedence in matters related to the underwater welding environment and work conditions.

The AWS D3b Subcommittee is working on providing additional guidance through generation of a non-mandatory commentary section to be included in the next revision of the ANSI/AWS D3.6 Specification scheduled for publication in 1997. The commentary is intended to provide the rationale for the specified requirements unique to underwater welding, as well as to describe the current state-of-the-art for users who may not be familiar with the topic.

3.3 Base Metals

Underwater welding standards have not stayed current with new materials presently used in offshore structures, ship building, power and other industry applications. In general the materials covered are carbon, low alloy, and austenitic stainless steels. This is a problem with the existing standards that will grow as high strength and other new materials become more prevalent.

3.4 Welding Processes

The primary welding processes covered in present underwater welding standards are gas metal arc welding (GMAW), gas tungsten arc welding (GTAW), flux cored arc welding (FCAW), plasma arc welding (PAW), and shielded metal arc welding (SMAW). Other processes are not restricted as long as they qualify in accordance with the governing standards. The SMAW and FCAW weld processes are the only two processes that apply to both wet and dry underwater welding.

The problem that exists is the lack of qualification criteria that is specific to other processes such as "Automatic Welding", "Friction Welding (e.g. Stud, Taper and Hydro Pillar Processing)", "Flash Butt Welding", and others. One shot pipe joining processes with narrow weld zones (e.g. laser and electron beam welding) are also not incorporated in present standards. Committees who draft and maintain underwater welding standards, such as the AWS D3b Subcommittee for underwater welding need to link with special industry groups to obtain the information required to draft sections for welding processes not currently addressed.

3.5 Definitions, Welding and NDE Symbols

Fortunately definitions, welding and NDE symbols related to underwater welding have remained consistent among all of the underwater welding documents. The AWS D3b Subcommittee is working on providing additional information on welding definitions, symbols, etc. in the non-mandatory commentary section to be included in the next revision of the Specification. A section on accepted practice for underwater weld symbol designation is also needed in the commentary.

3.6 Safety and Health

One of the key complaints from industry is the lack of safety and health information specific to underwater welding in the existing standards. The participants who draft, maintain and revise the standards feel that safety and health as related to underwater welding is a big enough field to warrant its own document. Others believe safety and health considerations need to be a part of the governing standard. The AWS D3b Subcommittee is working on providing additional information on underwater welding safety in an information (non-mandatory) annex to be included in the next revision of the Specification.

3.7 Standard Units of Measure

U. S. underwater welding standards until recently have used "standard units" as the primary unit of measure. To comply with international standards, U.S. standards are now including SI units. The AWS Subcommittee has included both standard and SI units in the latest revision of the ANSI/AWS D3.6 Specification. The problem in converting standard to SI units, is that a soft conversion does not generally facilitate use of relevant metric standards for testing and inspection. To be accepted internationally, quantitatively different SI unit values of measure must be used, instead of a soft conversion from British to metric units of measurement. The AWS D3b Subcommittee is working with the IIW SCUW to incorporate metric dimensions from applicable ISO standards where a soft conversion is inappropriate.

3.8 Referenced Standards

More effort must be made by the various organizations who produce underwater welding standards to work together in standardizing references to foster consistency and uniformity in the basic principles of underwater welding in keeping with ISO requirements.

4.0 DESIGN

Presently underwater welding standards do not include recommended practice, guidelines or other information related to design of underwater weldments. Design criteria are typically regarded as a customer determination. It cannot be over emphasized that design guidance must be addressed using a ***total system approach*** (e.g. design, engineering, planning, qualification, production, operation, inspection), not just a focus on the materials issues. This has been, and continues to be, an issue with participants who develop and revise underwater welding standards. Engineers responsible for drafting specifications and procedures, determining technical feasibility, costs, associated risks, project planning and other key issues often rely upon design standards to make critical decisions. There is a need for underwater design standards that address, as a minimum, the following key elements:

4.1 Technical Feasibility

More information is needed on various underwater environmental and operational conditions that are crucial in determining a underwater designs technical feasibility. A design standard, or related commentary, should provide sufficient information so that users can determine the most viable and cost effective repair solution (e.g. wet weld vs. dry weld vs. mechanical repair vs. no repair).

4.2 Load and Resistance Criteria

Load and resistance are the key elements in any weldment design. The possibility of service failure, relative to changes in the environment, increase if critical elements are not considered. Items that are needed in today's standards include:

- What is appropriate environmental (wave/seismic/ice/mud-slide) load criteria?
- Should original design loads be the basis (even if 25+ year return period storm criteria is used?) or draft section 17, API RP 2A-WSD? Should the weldments(s) be designed for the maximum capacity of the incoming brace (strength, not stability)? What are the limits?
- Should failure consequences be considered? What methods are recommended? What level of detail in the failure analysis process is adequate? Elements related to the consequences if a weld fails need to be established.
- What weld allowable should be used when considering resistance factors?
- Should weld allowable be the same as air? 75%, 50%, 40% reduction? Should reduction be a function of base metal quality, and consumable used?
- What NDE methods and acceptance criteria can be used during production to permit / justify an increase in weld allowable stresses.
- Should any reduction in allowable weld stress be verified or tied to procedure qualification results? (e.g. if a wet weld procedure can qualify to 3T bends, could higher design allowables be applied than if it could only pass the 6T bend test?)

These and other considerations related to load and resistance factors need to be addressed in order to improve design criteria for underwater weldments.

4.3 As-Is Condition

Standards need to emphasize the importance of good fit-up, what constitutes good fit-up, the need for careful as-is geometry measurements and suggestions on various ways to obtain measurements (e.g. templates, angle measurers, inspection techniques, etc.) to assist the engineer in developing design specifications. The importance of acquiring as-is base metal characteristics (e.g. toughness, through thickness, magnetism, pressure differentials, etc.) and through coupon extraction needs to be emphasized, as well as methods to obtain this information if it is not available.

There is a need to establish component performance data for underwater welding. An industry study is suggested as the first step to obtain useful performance information for underwater weldment design.

4.4 Design Considerations

There is a need for recommended practices that focus and expand on design considerations for underwater weldments. Operational information is needed for dry welded repairs using habitats, such as habitat design, lift factors, methods of anchoring and sealing the habitat, distributing loads and other concerns.

Guidelines are needed to obtain the desired results when considering wet welded repairs, such as:

- Should groove welds be altogether avoided? Should only doublers with fillet welds be used in wet weld applications?
- What should the carbon equivalency be in doublers used?
- Should wet welds in splash zone areas be prohibited?
- What wet weld techniques are recommended (stringer vs. weave, etc.)?
- Should wet weld symbols be marked to differentiate them from dry welds?
- What is acceptable to industry and regulators concerning lowering reliability targets and for what applications? (e.g. existing versus new structures, or when can a Class "B" weld be used vs. D1.1 surface weld criteria or equivalent for structural welding?
- To what extent can design adjustments be made in the field to facilitate a good fit-up?
- Is Class "A" weld criteria found in the ANSI/AWS D3.6 Specification equivalent to requirements in the ANSI/AWS D1.1 Structural Welding Code? When is it prudent to use ANSI/AWS D3.6 Class "A" as opposed to ANSI/AWS D1.1 surface welding criteria?
- It is important that input from the diving contractor be solicited as an integral part of the design process, yet this is not illustrated in any of the present standards.
- When can dis-similar metal welds be considered? What corrosion or other preventive measures should be taken if they are used?

4.5 Operator Considerations

There is a need to include operator considerations in future standards. The operator working in an underwater environment is subjected to a number of constraints not considered in surface welding environments, such as positioning while working within the confines of a habitat, or being subject to wave action during wet weld operations. More information is needed in this area to promote design modifications that reduce weld in the overhead position for wet weld applications, incorporate rounded vs. square corners in doubler design to facilitate laying continuous weld beads, design details with scallops to facilitate hydrogen release by keeping weld size small, and other considerations.

4.6 Quality Assurance

Guidance is needed regarding what inspection methods to use for various applications and the extent of inspection to be performed. Should the inspector be present for fit-up and deposition? Should the degree of inspection be linked to the class of weld? What can the inspector expect to encounter when verifying design compliance in underwater fit-up situations? What methods are recommended to ensure the design specifications are met (e.g. example inspection plans, video referencing, etc.) An industry study is suggested to establish guidelines for quality repairs by incorporating simulated mock-up component testing.

Procedures are needed for carbon equilivant testing that define minimum weight and other considerations that directly effect the sample taken for testing (e.g. sampling techniques, specimen and equipment treatment, calibration, etc.). Sourcing for comparable materials for production is also needed to assist users in finding compatible carbon equilivant materials.

The AWS D3b Subcommittee is including an informative section on design to be included in the (non-mandatory) commentary section of the next D3.6 Specification for Underwater welding.

To satisfy many of the above stated needs it is suggested that the following industry projects (studies) be funded.

1. "A Compendium of Underwater Welding Usage, Lessons and Costs": A study intended to compile the uses of underwater welding repairs in recent major repair projects. These projects will be analyzed, and the application (e.g. causes of damage, intent of repair, other repair options considered, design criteria used. etc.), lessons learned, and total repair costs, will be summarized per project. Company names will be kept confidential. Estimated Cost: $40,000.00. Estimated duration: 1 year. Suggested researchers: Independent underwater repair consultants, engineering consultants, or commercial diving contractors with underwater repair experience.

2. "Assessment of published joint wet weld testing conducted by SEACON JIP". Study of data - heat effected zone, static plus fatigue, plus fracture tests, porosity on real-life test specimens generated by SEACON in early 80's JIP. Never published, confidentiality has expired. Estimated cost $30,000.00. Suggested researchers: Global Industries.

3. "Study of Underwater Repairs as a part of Platform Salvage Operations". Study available data related to aged repairs performed on platforms being salvaged. Former repair welds will be analyzed using destructive and non-destructive techniques to determine characteristics, and integrity of the welds over time. Data collected to be accumulated updated and revised as old platforms are salvaged. Organization conducting study to maintain database of current underwater repairs being performed and monitor same in anticipation of the platform being salvaged at some future date. Study location: Gulf of Mexico. Duration: Ongoing. Estimated Cost: $10,000.00 per platform (subject to extent of repairs to be tested). Suggested Researchers: Louisiana State University in conjunction with the ongoing rigs to reef program.

4. "Fatigue Analysis of Underwater Wet Welds" Establish a fatigue test and evaluation of one or more underwater weld repair mockups. Test parameters and data to be collected to be determined by a qualified fatigue testing laboratory. Suggested Researchers: Stress Engineering Services - Houston, TX. Estimated Cost: $195,000.00 Estimated Duration: 1 year

5.0 WORKMANSHIP

Workmanship requirements of existing underwater welding standards, in general, vary according to application, method and type of weld.

5.1 Base Metal Preparation

Problems with base metal preparation in an underwater environment range from corrosion, coatings, lamination, to other undesirable factors such as marine growth. As a general rule base metals are prepared in accordance with an approved weld procedure and/or in accordance with the applicable standard(s) that apply. Related processes such as removal of weld metal or portions of base material are generally left up to the customer to approve. The problem with existing standards is that they generally do not address weld removal methods which require application of strict procedures to ensure that the integrity of the base metal is maintained during base metal preparation. Grinders are not as efficient in the water as they are on the surface and some grinding disks are not suitable for use in underwater environments. The AWS D3b Subcommittee needs to include accepted practice of base metal preparation in its new commentary.

Thermal techniques such as underwater cutting and gouging, leave heat affected zones and residue which must be removed before welding. Pneumatic or hydraulic chipping hammers that gouge out the weld metal have been known to cause micro cracking in the base metal that also must be removed prior to welding.

More information on the pitfalls that are unique to underwater welding base metal preparation and inspection is needed in future standards.

5.2 Assembly

Tolerances for underwater weld preparation and joint fit-up are generally developed during the procedure qualification. Additional emphasis is needed to describe proper pre job planning and the assembly constraints the welder diver is subjected to in the field vs. the more ideal open water tank or simulation chamber conditions used for qualifications. The AWS D3b Subcommittee needs to include a precautionary statement in its new commentary regarding assembly issues.

5.3 Confirmation Weld

As a general rule confirmation welds are made to test the worksite welding system to ensure the system is conforming to the qualified weld procedure, not requalify the procedure or welder. A clearer definition and description of confirmation welds is needed to avoid misunderstanding its purpose. The D3b Subcommittee need to consider eliminating the term "Confirmation Weld" and substitute "System Function Test" as a permanent solution.

5.4 Dimensional Tolerances

Similar to assembly requirements described in item 3.2 above, underwater weld preparation and joint fit-up are generally developed during the procedure qualification.

5.5 Weld Profiles

Weld profiles for underwater standards are generally equivalent to surface. Additional emphasis needs to be put into defining video inspection parameters and/or guidelines for inspecting weld profiles for the surface welding inspectors (e.g. low visibility, video panning guidelines, etc.).

5.6 Tack Welds and Temporary Welds

Tack welds and temporary welds are generally subjected to the same qualification requirements and acceptance criteria as the final welds in existing underwater welding standards.

5.7 Repairs

When addressing repairs two topics of discussion come to mind, weld repairs and structural or facility repairs.

There is relatively little information in existing standards that address the recommended practice or requirements for structural repairs and inspection. considerations such as the spectrum of conditions imposed by the environment, structural response to environment, design details of the structures involved, field operational and inspection requirements, and the service history or geriatrics information on past structural performance all play an important role in ensuring successful inspection and repair programs.

One problem with repairs, which is common to other elements of underwater welding, is lack of high quality technical data upon which to base comprehensive inspection and repair programs. More work needs to be done (perhaps in a non-mandatory commentary or appendix) to educate users that since most repairs are site specific, qualified weld or repair procedures alone are generally insufficient to ensure desired weld repair results. Too often operations, engineering and inspection groups work independently from one another in developing critical repair procedures. This can lead to procedures that are unrealistic for field operations, insufficient inspection criteria or key factors such as rate of deterioration, remaining life, performance and service history of the structure, and environmental conditions being omitted from consideration.

A recommended practice and/or guideline, based on sound collective data should be developed in order to improve the state of the art of structural and facility inspection and repair. Follow-up (e.g. frequency) of inspection of repairs also needs to be defined.

5.8 Peening

The decision on whether to use peening is generally left up to the customer. Peening technology has advanced in recent years to include ultrasonic peening. There is insufficient historical data presently available to adequately define requirements for these new technologies; however they should be followed and applicable criteria added into standards when sufficient data does become available.

5.9 Arc Strikes

Arc strikes outside the area of permanent welds are generally unacceptable by existing underwater welding standards. It is suggested that reference information on the undesirable effects and consequences of arc strikes be incorporated in future standards to encourage stronger preventive measures. The AWS D3b Subcommittee is developing additional information on arc strikes in the non-mandatory commentary section to be included in the next revision of the ANSI/AWS D3.6 Specification.

5.10 Weld Cleaning

Weld cleaning requirements are addressed in existing standards. However, little or no guidance is provided in cleaning methods and techniques needed to preserve and prepare surface finishes for inspection and non-destructive examination. The D3b Subcommittee need to specify conditions unique to underwater weld cleaning for NDE testing and re-evaluate whether general considerations regarding weld cleaning are adequate.

6.0 TECHNIQUE

Technique is a critical element of any underwater welding operation, yet in general existing standards address only the basic essentials.

6.1 Filler Metal

Filler metal requirements are generally specified in the manufacturers recommended practice and always in the applicable welding procedure. More information on filler metals, for both dry and wet underwater welding, needs to be included in applicable standards as reference for those responsible for developing and qualifying underwater welding procedures.

The AWS D3b Subcommittee need to include an explanation in the new commentary explaining why filler metals are required to be satisfied by manufacturer type as an essential variable in the AWS D3.6 Specification (e.g. AWS D1.1 does not have or need this requirement because classification of electrodes has been established). In addition, there is a need for the AWS D3b Subcommittee to evaluate the possibility including a special classification of underwater welding consumables and consider adequate supplemental testing in lieu of special classification (e.g. all-weld-metal-testing, etc.). More work is also needed between the IIW SCUW and the AWS D3b Subcommittee on wet consumable guidelines.

6.2 Measurement of Variable Conditions

Variable conditions such as welding current, arc voltage, shielding gas composition, etc., are established when qualifying the welding procedure and verified fairly easily. However, it is difficult to positively quantify indirect variables at the worksite that affect underwater welds, such as water current, water temperature, diving mode, visibility, background gas, etc. More information is needed in existing standards to provide requirements or recommended practice as applicable to improve the state-of-the-art in treatment of indirect variables. The AWS D3b Subcommittee is developing additional information on indirect variables in the non-mandatory commentary section to be included in the next revision of the ANSI/AWS D3.6 Specification.

6.3 Weld Temperature Control

Weld temperature control has and continues to be a constraint in both dry and wet underwater welding. Weld temperature control ranges are generally recorded during the weld procedure qualification. However temperatures qualified under controlled conditions may not be attainable at the worksite. More information on temperature control needs to be incorporated into underwater welding standards to avoid qualifying procedures that specify temperatures beyond what may be attainable at the worksite.

7.0 QUALIFICATION

7.1 Procedure Qualification

Just like surface weld qualifications, underwater Weld Procedure Specifications must undergo procedure qualification and testing which must be documented on a Procedure Qualification Record prior to any production welding. Existing standards generally require that weld test coupons be produced under actual or simulated site conditions. Underwater welding standards differ in-so-far as essential and nonessential variables. There is a need to resolve the imbalances between testing and field operation (e.g. define where to draw the line when field conditions are not the same as conditions simulated during testing).

The same variables that effect surface welding apply in addition to other variables unique to underwater welding, such as depth, environment and other considerations. Problems that arise with procedure qualification are the potential inconsistencies between the qualification and production weld conditions. Caution must be taken to ensure that weld umbilicals, shielding gas, consumable transport, background gas, depth, etc. are simulated properly during procedure qualification or the production weld may not be able to meet procedure requirements.

The AWS D3b Subcommittee is developing sample WPS and PQR forms, for both dry and wet welding, to be included in the next revision of the ANSI/AWS D3.6 Specification. Each variable indicated on the forms will include a paragraph or table item number to aid in finding its reference in the document.
Generally variables such as dive mode, current, wave action, visibility, and other such conditions that may indirectly effect weld integrity are considered nonessential. More work is needed to separate indirect from direct variables in existing standards without reducing the importance of the indirect variables in the process. The AWS D3b Subcommittee plans to keep reference to indirect variables in the body of the D3.6 Specification but to expand the information related to indirect variables in the non-mandatory commentary section to be included in the next revision of the Specification.

7.2 Welder Qualification

Welder performance tests for underwater welding like surface welder qualification are intended to establish the welder's ability to make sound welds using a qualified welding procedure. Variables such as welding mode or exposure to water, change in type of diving suit protection, visibility, thermal environment, and other considerations are added to the welder qualification requirements. Tests are generally performed under simulated conditions however qualifications at the production site are allowed.

Like procedure qualification, problems that arise with welder qualification are the potential inconsistencies between the qualification and production weld conditions especially true for wet weld operations. Site conditions do not remain the same for day to day. Changes in tide, current, weather, etc., affect the conditions to which the welder diver is exposed. Simulations cannot take into account every contingency that will be experienced in the field. More information is needed in existing standards to provide guidance (perhaps in a non-mandatory commentary or appendix) to improve how the user responds to typical changes in site conditions.

8.0 INSPECTION AND TESTING

Generally inspection and testing requirements for underwater welding in existing standards are designed to ensure materials, qualifications, fabrication, and examination conform to the governing standards. Inspection and testing requirements cover a range of critical components to include but not limited to:

- Materials
- Procedure Qualification
- Equipment
- Performance Qualification
- Production
- Records
- Personnel Qualification
- Other Considerations

8.1 Underwater Welding Inspector

One of the problems with the inspection of underwater welds and related components is the qualification of the inspectors themselves. Qualified surface welding inspectors are not necessarily qualified to inspect underwater welds. To date there is no certification program to qualify inspectors for the unique constraints that are common to inspecting in underwater environments. Inspections are often performed under low visibility and other conditions that challenge the inspector. The inspector must be comfortable listening to and communicating with personnel in the water, visually inspecting through the use of video systems, and must be cognizant of conditions that may prohibit obtaining desired results and other considerations. The AWS D3b Subcommittee is working with the AWS Q&C Committee to introduce a supplementary CWI examination for underwater welding inspection personnel before publication of the next D3.6 Specification. The examination will include practical questions to verify the inspectors ability and familiarity with underwater inspection and quality imaging.

8.2 NDE & Testing

The primary NDE methods used for underwater welding are Visual, Radiographic, Ultrasonic, Magnetic Particle and Eddy Current Examination. Users of existing standards complain that NDE requirements are too general. More work is needed to tailor NDE requirements to underwater applications, perhaps through either a non-mandatory commentary or an appendix to educate the user on conditions unique to underwater inspection, constraints that effect obtaining the desired inspection results and practical examples that may help the user to overcome the constraints.

Techniques / methods to improve image quality in underwater inspection need to be provided, such as new tools to aid the inspector in verifying image quality (e.g. similar to RT penetrameter instruments) with accompanying standards.

There is a need for testing criteria in existing standards to become consistent in-so-far as type and method of testing, specimen preparation, accept/reject criteria, and other considerations. As previously stated in item 3.7 (Standard Units of Measure) more work needs to be done to identity, and incorporate by reference, internationally accepted metric standards for specific testing methods. Standards have fallen behind in providing requirements for new or alternative testing methods that have established a performance history, such as crack opening displacement (COD) testing and other methods that can improve the state-of-the art of verifying achievement of desired physical properties through mechanical testing and examination.

SUMMARY

Presently the state of standards, specification and codes for underwater welding and inspection is good. While there is still much work to be done, organizations responsible for drafting, maintaining and revising underwater welding standards are working together more now than ever before.

It is not feasible for any one document to include comprehensive requirements for every issue or problem related to underwater welding, however work is in progress to meet the requirements of key industry needs in such areas as design, safety and health, new processes, compliance with international standards, additional information on workmanship, technique, weld procedure and personnel qualification, inspection, testing and more. Participants are discussing the need to draft improved standards that will address industry problems that go beyond the scope of the underwater welding standards, such as underwater cutting, structural design, filler metal specifications, in-water safety, certification programs, etc. Joint industry projects to address these issues are also being recommended. Different industry organizations are being encouraged to initiate or expand a dialogue with committees to advance the state of the art underwater welding, such as: the IIW Select Committee on Underwater Welding, AWS D3b Subcommittee for Underwater Welding, API and others.

Like any other standard, specification or code, underwater welding standards cannot exist or progress without the time and commitment volunteered by participants experienced and knowledgeable in the field of underwater welding. Developing and implementing a successful international standard will require a cooperative effort of organizations composed of owners, operators, contractors, inspection/testing, educators/institutes and government representatives working together in the spirit of consensus toward a common goal.

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WELDING CONSUMABLES AND WELDABILITY

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SUMMARY

The degradation of the mechanical properties of underwater wet weldments can be related to the fact that the welding arc is immersed in the aqueous environment. The decomposition of water during the welding process, as well as its ability to remove heat from the welded area, is responsible for several problems.

The factors affecting the mechanical properties and service performance of underwater wet welded joints are identified in the paper. The effects of welding variables, water pressure, type of electrode covering are also presented.

Although several successful repairs have been made using wet welding process, it is felt that to achieve more significant progress in wet welding, consumables with superior properties must be developed. It is not the intention of the authors to prepare an exhaustive and detailed description of all the problems related to underwater wet welding and the consumables used in wet welding. Instead, it is the hope of the authors that the information

presented in this position white paper may serve as subsidy for discussion among the specialists (welding engineers, consumables manufacturers and welding researchers) such that non-traditional, innovative ideas for quantum improvements in underwater welding consumables can be reached.

1. PROBLEMS ASSOCIATED WITH UNDERWATER WET WELDED JOINTS

Mechanical properties and service performance of underwater wet welded joints are related to the occurrence of physical (cracks, pores) and/or metallurgical (hardness, microstructure) discontinuities in the weld metal or heat affected zone (HAZ). The main problems encountered in underwater wet welds are:

- Base metal heat affected zone cracking
- Weld metal hydrogen cracking
- Alloying element loss in weld metal
- Weld metal porosity
- Weld metal solidification cracking

1.1 Base Metal Heat Affected Zone Cracking

Cracks can exist in a weldment as: base metal HAZ hydrogen cracks, weld metal hydrogen cracks and weld metal solidification cracks. Cracking susceptibility of a weldment is dependent on its microstructure, which is affected by both chemical composition (hardenability) and cooling rate. High hardenability in carbon steels (CE > 0.40 wt. pct.) was found detrimental to HAZ hydrogen cracking (Grubbs and Seth, 1977). As such, fabricators select low CE materials wherever possible to avoid cracking. With the increasing use of higher strength materials in modern marine structures, however, alternate methods must be proposed to minimize cracking in these structures.

Cooling rate is strongly affected by the welding procedure used (heat input and weld joint design). In the presence of water, the cooling rates in wet welds are much higher than those obtained in dry welding. In conventional structural steel welds, the fast cooling can promote formation of constituents such as martensite and bainite, which are both high strength and brittle, and susceptible to hydrogen cracking. Multipass welding, with high degree of overlapping, is beneficial in decreasing hardness and improving toughness, as illustrated in Figure 1.

More specifically, base metal cracking is caused by the simultaneous occurrence of the following factors (Yurioka and Suzuki, 1990):

- Critical concentration of diffusible hydrogen at the crack tip
- Microstructure susceptible to hydrogen cracking
- Stress intensity of sufficient magnitude
- Temperature lower than about 200°C

These conditions are easily met in underwater wet welding. As a result of the last factor, the term *cooling time to 100°C* related to hydrogen diffusion was devised.

1.1.1 Critical concentration of diffusible hydrogen at the crack tip

Surrounded by water, significant amount of hydrogen is generated by the decomposition of water and absorbed by the weld pool. As temperature decreases during weld solidfication, the large amounts of hydrogen in the weld pool diffuse into the adjacent base metal heat affected zone. Thus, higher initial hydrogen concentration in the weld pool will also result in higher hydrogen content in the heat affected zone. The diffusible hydrogen content of a weld metal will depend on:

- Electrode coating - Type and thickness
- Water depth (pressure)
- Heat input

Stalker (1977) and Gooch (1983) determined that oxidizing electrodes deposit wet welds with diffusible hydrogen lower than rutile and basic electrodes. Some results obtained by Gooch are shown in Figure 2. This behavior seems to indicate a hydrogen-oxygen control relationship in the weld pool.

Hoffmeister (1983) found that increasing the coating thickness of electrode results in more hydrogen pickup. However, this effect may not be a direct effect since increasing electrode coating thickness also affects the arc stability and melting characteristics of an electrode.

Ando and Asahina (1983) observed that the diffusible hydrogen of wet welds decreased as depth of welding increased, as shown in Figure 3. This observation can be related to the results developed by Ibarra, Grubbs and Olson (1987), and shown in Figure 4, that as water depth increases the weld metal oxygen content increases while the amount of deoxidizers decreases. This correlation also supports the results obtained by Stalker (1977) and Gooch (1983) using oxidizing electrodes that high oxygen welds have lower diffusible hydrogen (Figure 2).

The effect of increasing heat input on decreasing (slightly) diffusible hydrogen is shown in Figure 5a (Hoffmeister, 1983).

1.1.2 Microstructure susceptible to hydrogen cracking

As indicated earlier, structural steel weld metal microstructures of high strength and low toughness such as martensite and upper bainite are more susceptible to hydrogen cracking. The formation of these phases in the heat affected zone will depend on:

- Base metal chemical composition
- Weld metal chemical composition
- Heat input and cooling rate
- Water temperature
- Water pressure

Not only the base metal chemical composition is important in determining the heat affected zone cracking susceptibility, the weld metal also plays an important role. This statement is particularly true when fusion boundary cracking is considered. Being an extremely strategic region, cracking along the fusion boundary can lead to heat affected zone cracking. An example is the use of weld metal with austenitic stainless steel compositions on ferritic steel plates. Cracking has been reported along the fusion boundary, region where high dilution can promote the formation of brittle martensite (Stalker, 1977 and Gooch 1983).

As shown in Figure 6, welding heat input also has a substantial influence on the cooling time between 800 and 500°C, $\Delta t_{800\text{-}500}$. Notice that for the range of heat input normally used in wet welding (1.0 to 2.0 kJ/mm) the cooling time is very short, only 2 to 4 seconds. Hasui and Suga (1981) showed in Figure 7 that $\Delta t_{800\text{-}500}$ decreases with increasing base metal thickness. However, the cooling time remains constant at approximately 2 seconds for plate thicknesses above 15 mm. They also observed that cooling rates at the weld start and crater are higher than those measured in the mid-section of the bead where the process works in a quasi-steady state regime as shown in Figure 8. The significance of this is that the extreme points of the weld bead, especially the crater, may be more susceptible to hydrogen cracking. Longer cooling time (increasing heat input) reduces the HAZ hardness as shown in Figure 5b (Hoffmeister, 1983). Tsai and Masubuchi (1979) recommended low welding speeds as an effective way to reduce cooling rates in HAZ.

Contrary to general belief, water pressure (depth) and water temperature have only a small effect on the $\Delta t_{800\text{-}500}$ measured in the HAZ as shown in Figures 9 and 10, respectively.

1.1.3 Stress intensity

The applied loading condition, the characteristics of the defects that are present in the weldment, and the strength of the weldment (base metal, heat affected zone and weld metal) all affect crack propagation in a weld joint. However, the local stress acting in the region of crack initiation, rather than the nominal stress, is the parameter that controls the incidence of hydrogen cracking. Local stress can be defined as the nominal stress multiplied by the stress concentration factor (K_t). Stress concentration factors at the root of weld varies with the joint geometry and can be as high as 6.9 for single bevel - type K groove (Yurioka and Suzuki, 1990). The weld bead geometry less susceptible to hydrogen cracking, regarding this aspect, is the bead-on-plate weld.

Weld metals with lower strength (even or undermatching conditions) will induce less deformation on the HAZ region thereby reducing its susceptibility to hydrogen cracking. Data taken from the work of Nóbrega (1981), plotted in Figure 11, show that high weld metal hardness can be detrimental to HAZ integrity. Under the condition of overmatching, hydrogen cracking can occur even for weld deposits with low diffusible hydrogen. The best results were obtained with the low weld metal strength and low diffusible hydrogen combination, which may be achieved with oxidizing electrodes.

It can be demonstrated that both modulus of elasticity and yield strength decrease with increasing porosity. The effect of porosity on the HAZ hydrogen cracking has not yet been experimentally verified, but one can speculate that porosity, by reducing the residual stresses, may decrease the susceptibility to HAZ hydrogen cracking.

1.2 Factors Affecting Weld Metal Hydrogen Cracking.

The same factors that affect HAZ cracking will control weld metal hydrogen cracking. In the case of weld metal, however, composition and microstructure play an even more important role. If the hardenability of the weld metal is higher than that of the base metal it is likely that austenite decomposition will occur first in the base metal HAZ. The lower hydrogen solubility of ferrite in the heat affected zone will hinder the diffusion of hydrogen out of the weld metal (still austenite at this point). The retention of hydrogen in the weld metal increases the cracking susceptibility of the weld metal when it finally transforms into martensite or bainite. Figure 12 shows weld metal hydrogen cracking in wet welds deposited with rutile electrodes. An important feature in the weld metal hydrogen cracking is that it occurs in planes perpendicular to the direction indicated in the figure (transverse planes). Therefore, weld metal hydrogen cracking is not effectively detected by microscopical examinations of transverse section. Instead, longitudinal or normal sections must be used for this purpose.

1.3 Alloying Element Loss in Weld Metal

1.3.1 Effect of Water Pressure

The aqueous environment affects profoundly the weld metal chemical composition. With the decomposition of water, which releases oxygen and hydrogen, alloying elements that form thermodynamically stable oxides will be easily oxidized and transferred to the slag. This loss of deoxidizers such as manganese and silicon increases as depth (pressure) increases. Weld metal oxygen content, however, behaves in a slightly different way. The initial increase of oxygen with pressure is followed by a range of insensitivity for greater pressures, as shown in Figure 4. The effect of water pressure on weld metal composition reported by Christensen (1983) is similar to that reported by Ibarra, Grubbs and Olson (1987) and is shown in Figure 13.

Carbon can decrease or remain constant (Christensen, 1983), or can increase to a constant value (Ibarra, Grubbs and Olson, 1987). The weld carbon content variation with pressure obtained by Ibarra, Grubbs and Olson (1987) is shown in Figure 14. The increase in weld metal carbon content with depth is attributed to the carbon monoxide reaction due to the presence of calcium carbonate in the flux (Sanchez Osio et al., 1993). In the results reported by Christensen (1983), shown in Figure 13, weld carbon contents remain at constant level.

Nickel, copper and other stable metals are not expected to be significantly affected. The loss of alloying elements and iron (this when all the deoxidizers are consumed) by oxidation also leads to the formation of excessive amount of slag which often result in slag entrapment and impair the out-of-position welding capability of the process.

As a consequence of these changes in chemical composition the microstructure also varied with depth but stayed constant below a specific depth. For the electrode tested this behavior occurred for depths below approximately 50 m (164 ft) with a microstructure consisted of grain boundary ferrite, ferrite with second phase aligned and oxide inclusions. Similar results were found by Wood and Bruce (1991).

1.3.2 Effect of Electrode Covering

Oxygen can be maintained at approximately 500 ppm with additions of Ti and B to rutile electrodes as shown in Figure 15 (Sanchez-Osio et al., 1993). Comparing with the usual concentration of around 1000 ppm, this reduction of oxygen represents significant control of the weld pool chemical reactions. Oxidizing electrodes usually result in welds with low Mn, Si and C contents. Recently Pope, Liu and Olson (1994) found that the oxygen content of UWW welds increases to a constant value of approximately 2000 ppm as the electrode covering becomes more oxidizing in nature by the addition of hematite (Figure 16). The reason why the oxygen remain constant at this value can be understood with the help of the Iron-Oxygen phase diagram, shown in Figure 17 (van Vlack, 1977). It can be seen that when the oxygen content of the weld system is higher than 0.17 wt. pct. (1700 ppm), two immiscible liquids, Fe (the liquid weld metal) and FeO (the liquid slag), are formed at temperatures close to the solidification temperature. Solidification occurs by a monotectic reaction where liquid iron decomposes into solid iron and liquid FeO. As a result, the weld metal content will remain constant at a value close to that of the monotectic point, no matter what is the oxygen content of the system.

The data shown in Figure 4 can be replotted in a ternary Fe-Mn-O diagram, as the one shown schematically in Figure 18, where it can be seen that as depth increases the weld metal composition tends to one very similar to that of oxidizing electrodes, with a constant oxygen content and low manganese (or silicon).

1.4 Weld Metal Porosity

Underwater wet welds are known to contain substantial amounts of porosity. AWS D3.6 specification defines the permissible amounts of porosity, their size distribution and density in underwater wet welds. Pores of diameter greater than 5 mm are not allowed. Pores of diameter between 5 and 1.6 mm are restricted to 7 per inch weld length per inch plate thickness. There is no restriction concerning pores smaller than 1.6 mm diameter. Suga and Hasui (1986) determined that the main gas present in pores of welds deposited by rutile, ilmenite or iron-iron oxide electrodes is H_2 (97%). Other gases such as CO, CO_2 and CH_4 were also detected. The main factors affecting weld metal porosity are:

- Water depth (pressure)
- Electrode covering
- Arc stability

1.4.1 Water pressure

Ando and Asahina (1983) detected that welds performed at greater water depths (pressure) exhibited lower densities, Figure 19, and attributed this loss of density to the formation of internal porosity. According to Suga and Hasui (1986), porosity starts at approximately 0.5 kg/cm^2 (5 m water depth) and increases with increasing depth as shown in Figure 20. At a depth between 20 to 30 meters the shape of the pores changes from an approximately spherical morphology (type-A or "hydrogen concentration pore") to a more elongated one (type-B or "bubble type pore").

1.4.2 Electrode covering

Results from Ando and Asahina (1983), and Suga and Hasui (1986) show that the electrode covering has an effect on the amount of porosity present in the weld metal. Some electrodes are more sensitive to depth than others. Sanchez-Osio, Liu and Olson (1993) showed that the amount of porosity of welds deposited at 10 m can be minimized with an addition of approximately 12.5 wt. pct. of calcium carbonate to the electrode covering, Figure 21.

Few experimental data exist relating the effects of porosity on the mechanical properties of UWW welds. Research work carried out on sintered iron and steel, where porosity is the main concern, can give some indication on how porosity will affect the mechanical properties of UWW welds. Figure 22 (Danninger et al., 1993) shows that porosity decreases the Young's modulus, yield and tensile strength, ductility and toughness.

Toughness and ductility are more affected by porosity than yield or tensile strength. Concerning fatigue crack propagation Matlock et al. (1983) determined that, at low applied stress intensity factors, pores are effective in pinning the crack front and retarding the crack propagation rate, Figure 23. For high applied stress intensity factors, however, they found that crack growth is accelerated in the presence of porosity. Their results agree well with those obtained by Esper, Leuze and Sonsino (1981) with sintered steels (Figure 24). The agreement of the two sets of data suggests that the mechanical behavior of porous underwater wet welds can be estimated using data gathered from sintered steel studies.

1.4.3 Arc Instability

Porosity can also result from arc instability. As the water depth (pressure) increases, the welding arc becomes more constricted and unstable. This phenomenon is related to the mobility of the charge carriers in the plasma. To maintain the electrical conductivity of the arc, higher voltage is required. The increase in voltage also leads to larger fluctuations in arc voltage. As a result, porosity and slag may be entrapped in the molten weld pool.

As attested by most underwater welding experts, welding in shallow depths is far more critical than in greater depths. Figure 25 supports the observation and shows that arc stability actually improved as water depth increased from 1.5 to 6 m (Nixon and Graham, 1993). However, as reported by Wood and Bruce (1991), the arc stability deteriorates again at greater depths.

Electrode diameter is also found to affect arc stability. This finding may be related to the arc instability with water depth and an increase in current density (smaller diameter electrodes) may be beneficial to increase the "rigidity" of the arc. Nixon, Stephen and Graham (1993) verified that 3.2 mm diameter electrodes were more stable than 4 mm ones in shallow water wet welding.

1.5 Weld Metal Solidification Cracking

In addition to tensile stresses acting in the weld region, solidification cracking in welds is affected by the following factors:

- Solidification Microstructure
- Chemical Composition
- Joint Geometry

1.5.1 Solidification Microstructure

Tsai and Masubuchi (1979) observed that, in wet welds, "the molten pool travels at a constant speed with the electrode and *the weld puddle* has a constant size of tear drop geometry". This type of pool geometry results from the surface heat losses in the weld area behind the arc. Savage and Aronson (1966) showed that weld pool geometry affects the mode of solidification growth. The tear-drop weld shape gives rise to competitive crystal growth where only a small number of favorably oriented grains are able to grow promoting a structure of coarse columnar grains meeting at the center line of the weld, which is more susceptible to segregation and solidification cracking. For surface welds this type of pool geometry is developed only at high welding speeds. On the other hand, the elliptical-shaped pool, characteristic of surface welds at low speeds, encourages the growth of grains with many different orientations promoting a finer microstructure

1.5.2 Chemical composition

As pointed out by Fredriksson (1976), Bhadeshia and Svensson (1993) the type and concentration of the alloying element as well as the cooling rate determine the first phase to solidify and, therefore, have an important influence on the final microstructure and susceptibility to solidification cracking. Addition of austenite stabilizing elements (C, Ni, Mn) to the weld can promote solidification via primary austenite even for low cooling rates. Nickel can be used as alloying addition to electrodes for UWW welding with two main purposes:

1. to obtain a weld metal with austenitic structure and thereby decreasing the amount of diffusible hydrogen (Stalker, 1977, and Gooch, 1983);
2. to improve the mechanical properties, in particular toughness, of low C, low Mn, high oxygen ferritic weld metals.

Pope et al. determined that the optimum nickel concentration in low carbon steel electrodes lies between 2 and 3 wt. Pct. Additions of Ni beyond 3 wt. pct. can cause solidification cracking in UWW welds (Pope, Teixeira, dos Santos, Paes and Liu, 1994).

Impurities such as sulfur have a deleterious effect in solidification cracking. Consumables for UWW welding should have low levels of impurities.

2. PROPOSED MEASURES TO MITIGATE UNDERWATER WET WELDING PROBLEMS

2.1 Hydrogen Cracking

The methods employed to reduce hydrogen cracking are based on the premise that the problem can be avoided if at least one of its controlling factors, for example, diffusible hydrogen content, residual stresses and hardness, can be minimized. Some of the procedures already experimented in wet welding include the use of one or more of the following techniques:

- Temper Bead
- In-Situ Post-Weld Heat Treatment
- Refractory Or Oil Putty Shielding
- Austenitic Steel Weld Metals
- Nickel Base Weld Metals
- Oxidizing Electrodes

2.1.1 Temper bead (Ibarra et al., 1991)

The temper bead technique consists in depositing a weld bead over a previous one. This second weld has to be deposited in such a way that its HAZ tempers the coarse grained region created in the base metal by the first weld before cracking occurs in the previous pass. The occurrence of cracking is decreased due to the hardness reduction in the base metal HAZ, and also to some decrease in diffusible hydrogen.

The temper bead technique, as it increases the amount of fine grained material, has also a beneficial effect on the impact properties of the weld. The main disadvantage of this technique, for underwater welds with high diffusible hydrogen, is that it is very dependent on the timing and positioning of the temper bead.

2.1.2 In-Situ Post-Weld Heat Treatment

A variant of this technique is the *double layer technique* which has been tested as method to avoid post-weld heat treatment of repair welds in pressure vessels (Jones, 1987.). In this case a first layer of low heat input (narrow HAZ) is placed on the bevels. In order to decrease the hardness of HAZ a second layer is then deposited with higher heat input.

The *In-situ post-weld heat treatment* (Szelagowski et al., 1992) technique consists of heating the weld with an oxy-fuel torch immediately (still under water) after its completion. The local increase in temperature decreases both the diffusible hydrogen content and hardness reducing the HAZ cracking tendency. Reduction in hardness of about 200 HV(0.2) and 73% in diffusible hydrogen (from 59 to 15 ml/100g weld metal) are possible.

2.1.3 Refractory or oil putty shielding (Suga, 1992)

This method consists in shielding the vicinity of the part to be welded from the water. The heat loss from the weld to the water is diminished and the cooling rate is lowered. The diffusible hydrogen is not affected by this technique but the reduction of hardness obtained is sufficient to prevent hydrogen cracks in some cases. Carbon pickup is possible and may require verification. However, the results of impact and bending tests are reported to improve.

2.1.4 Austenitic steel weld metals (Stalker, 1977 and Gooch, 1983)

The use of austenitic stainless steels weld metals for underwater wet welding was proposed based on the fact that hydrogen has high solubility combined with low diffusivity in the austenite. By this way the hydrogen is kept in the weld metal and the harder HAZ becomes immune to cracking. However, austenitic weld deposits are susceptible to hydrogen cracking along the fusion line and solidification cracking as well. The first type of cracks are associated with the formation of martensite in the area of high dilution. The large difference between the thermal expansion coefficients of base and weld metals, generating high residual stresses, is also important in both types of cracking (Ibarra and Olson, 1992).

2.1.5 Nickel base weld metals

Nickel base weld metals have thermal expansion coefficients similar to ferritic metals and, having the advantage of also being austenitic, are practically insensitive to hydrogen cracking. However, nickel electrodes, specially those with basic coatings (Gooch, 1983), have unstable arcs and give weld deposits with unacceptable levels of defects such as porosity and lack of fusion. This problem is aggravated as the depth of welding is increased and seems to be related to insufficient heat input delivered by the welding system to properly melt the nickel base consumable.

2.1.6 Oxidizing electrodes

Several investigators (Stalker, 1977; Nóbrega, 1981; Gooch, 1983) found that the hydrogen cracking in underwater welding could be avoided by the use of oxidizing electrodes. The results of hydrogen measurements on some electrodes tested by Gooch (1983) were shown in Figure 2. The basic and rutile electrodes have high levels of diffusible hydrogen and consequently can cause HAZ cracking more easily in underwater wet welding. The low diffusible hydrogen measured in the welds deposited by the oxidizing electrodes has been attributed to their higher inclusion content. However, as shown in Figure 2 the total hydrogen of welds deposited by oxidizing electrodes is much lower than those of basic or rutile electrodes. The explanation for this may be in the fact that the oxidized weld metal absorbs less hydrogen than the deoxidized ones. Small, Radzilowski and Pehlke (1973) observed that the rate of hydrogen absorption by liquid iron is decreased by the presence of oxygen. Being surface active, oxygen forms an ionic monolayer of Fe - O on the liquid surface that decreases the absorption rate of hydrogen.

2.2 Weld Metal Hydrogen Cracking

- Use ferritic weld metals with MS temperature higher than that of the base metal.

2.3 Weld Metal Solidification Cracking

- Use cosumables with low impurity levels.
- Limit amount of alloying elements that stabilize austenite (Ni, Mn, C etc.).

2.4 Weld Metal Porosity

- Use electrodes that control hydrogen and C-O reaction in the weld metal.
- Use limited amounts of calcium carbonate in the electrode covering.

2.5 Weld Metal Microstructure

- Alloy the weld metal to promote acicular ferrite formation in the region of columnar grains.

- Use high number of passes (high degree of overlapping) for grain refinement.
- Alloy the base metal to refine the grain in the reheated region.
- Use slag systems that retain heat efficiently to modify the thermal cycle.

2.6 Arc Stability

- Use rutile-based coatings.
- Use power sources with higher open circuit voltages (OCV). The experiments performed by Schmidt et al. (1991) using OCV up to 150 volts DC show some possibilities on the use of higher OCV for deep water welding.
- Use exothermic coatings.
- Use coating ingredients to improve plasma conductivity.

3. WELDING CONSUMABLES SELECTION AND DEVELOPMENT

It is clear from the previous sections that to improve the underwater wet weld properties and performance, much has to do with the material selection, in particular that of the welding consumables. Thus, it is timely to critically evaluate the commercially available consumables for underwater water and identify the needs for development. However, it is not the intent of this position white paper to attempt en exhaustive and detailed description of the current status of the development of welding consumables for wet welding.

The information available in the open literature can basically be grouped into the following categories:

- Effect of wet welding on the resulting weld metal properties.
- Advantages/disadvantages of using 'standard' types of consumable in wet welding.
- Behavior (both operational and from the point of view of weld metal properties) of 'standard' types of slag system, modified in one respect or another.

The term "standard types of consumable" is used here to refer to products designed for surface welding (in air) or under a gas protection at atmospheric pressure. The first two groups of publications are relatively numerous. However, most of the papers tend to be in a reporting format, with limited discussion and often divergent interpretation. Publications related to "standard types of slag system" are not very well documented and results are fragmentary. A comparative analysis of the more recent publications with previous publications does not show any real significant change in this situation. Therefore, the question of the availability of optimum suitable wet consumables/technologies remains open.

In the following discussion, an attempt has been made to identify some possible approaches for further development. Unless otherwise specified, the word "consumable' will mean covered electrodes.

3.1 Standard Covered Electrodes

Development of coating formulations for covered electrodes has been an ongoing process ever since this type of product was conceived. From the early stages on, it has been recognized that such coatings, depending on their operative and metallurgical characteristics can be grouped into classes, and classification standards have evolved.

A very well known example is AWS 5.1, covering notably those products that have been mostly used so far to carry out underwater wet welding in experimental as well as practical situations. Such classifications, with naturally some additions of types and variants as well as with some refinement in the classification criteria, have nevertheless remained basically unchanged with respect to the classification and designation of types of coating and/or slag.

Nowadays, after about a century of research and development, and while considerable amounts of effort continue to be invested in perfecting and optimizing electrode coating formulation, the situation can be characterized as follows:

- Delineation between type of coating belonging to different classes has become less crisp (more fuzzy) than used to be.
- Diversification within the same class remains a fact. There are in principle as many 6013, 7014 or 7018 electrodes as there are formulators.
- There is no such thing as "the" universal consumable capable of doing everything.
- An important number of available design/formulation options/avenues still remain open for further exploration.

3.2 Wet Welding

What has been said so far applies to covered electrodes welded in air at atmospheric pressure, an environment which we are familiar with and in function of which all the existent electrodes have been formulated. However, the underwater wet welding environment is drastically different in the following aspects:

- The effects of pressure as a function of depth in terms of:
  - Arc stability,
  - Modified partial pressures of gases in the arc column,
  - Shifting of chemical reactions (gas-metal and slag-metal).
- The effects of a considerable increase of hydrogen present in the arc atmosphere as a result of water dissociation in terms of:
  - Increased amount of diffusible hydrogen in the weld zone,
  - Increased risk of hydrogen embrittlement and cracking,
  - Increased risk of porosity.
- The effects of water environment as such, in terms of significantly increased heat transfer and cooling rates.

Despite all this, the most remarkable observation is that 'standard" consumables are able to operate at all in this new environment. Since, in terms of actual systematic development, the amount of effort that has been dedicated to consumables specifically designed for wet welding represents only a very small part of similar efforts that have been dedicated to the development of 'standard" consumables. It is logical to conclude that further research and development has good chances to turn current 'potentials' into improved practical and acceptable solutions to the problem of underwater welding.

3.3 Development of Wet Underwater Welding Solutions

The word 'solutions" here means consumables in general in combination or not with technologies and/or equipment. Considering first the covered electrodes, it is natural for the user who is confronted with a new set of conditions and requirements to opt in first instance for a "traditional' approach, in this case, the extension from air welding to wet welding. This transition is what has occurred with standard E6013, E7014 and E7018 grade electrodes. It is also logical, as a function of the accumulation of observations and knowledge, that "corrective actions" be implemented and "improvements" be attempted, such as: waterproofing, compensation of coating ingredients for Mn losses, addition of arc stabilizers, dilution of hydrogen through addition of extra amounts of carbonates, etc., to name but just a few of those that have been experimented with.

Based on reported experience, it does not seem that any major break through have been achieved in recent years. End users are still in search of products with desired performance, and meeting the targeted minimum weld metal properties. For a more substantial progress, some circles must be broken. In all probability, significant progress is not likely to be made without departing from the traditional approach, designs and formulations.

Grantham and Tsai (1992) proposed the addition of electrode coating ingredients that modify the surface tension of the molten metal/slag interface which improved the wet weld bead profile.

Daemen proposed the use of a tubular, rather than a solid electrode core wire, for underwater wet welding. Such design opens a number of possibilities and offers a series of potential advantages. For example, highly reactive materials can be concentrated in the core while other materials (essentially slag formers, eventually gas formers) constitute the coating. Also higher current densities can be achieved to help stabilize the arc. A comprehensive and comparative set of experiments has been carried out with products using this approach. Results were very encouraging. Further development along identified possible lines would however be needed.

Along similar lines of thinking, hollow tubular coated electrodes can be envisaged. During welding, an appropriate gas could be applied at an appropriate level of over pressure (function of depth) through the hollow core. The use of pulsed current has been attempted and some positive aspects that, however remain to be confirmed, have been identified.

Alternative types of consumables such as flux cored wires to be used with the MIG/MAG process cannot only be envisaged but have effectively been used, at least at an experimental level. Flux cored wires seem to offer good potentialities, but again, as with covered electrodes, a simple transposition from air to water is unlikely to lead to immediate success. The probability also is that the best chances of success will reside in an open approach calling upon imaginative new combinations of technologies. In this case, the Power Source Technology undoubtedly will need to be integrated into an overall satisfactory system. Both gas-shielded and self-shielded core wire designs can come into consideration, but it is the author's feeling that self-shielded designs may be more appropriate in first approach. The reason for this is that there is some similarity in the challenge that has led to their development. While wet welding is confronted with the challenge of reducing hydrogen levels generated from water dissociation, self-shielded arc welding was confronted with the reduction/stabilization of nitrogen present in the air.

4. SUMMARY OF WORKING GROUP DISCUSSION

4.1 Current Practice and Understanding

The analysis and discussion of the Working Group is summarized below. It is generally agreed that with respect to Base Metal Hardenability and HAZ Cracking, the following conclusions can be made.

1. Considering the steels that are currently in service in marine structures such as offshore platforms, CE_{IIW} is adequate for the prediction of cracking susceptibility. For the steels whose composition fall into the application range of P_{cm}, they do not usually present weldability problem.
2. To better define weldability using CEIIW, the following guideline is recommended. For steels that have carbon equivalent less than 0.40 wt. Pct., HAZ cracking is generally not observed. For steels between 0.40 and 0.46 wt. Pct., precaution steps must be taken to decrease HAZ hardness and hydrogen control. Examples of such steps include multiple temper bead technique, postweld heat treatment and electrodes with higher oxygen potential. It should also be pointed out that success in application of these techniques to your practice is dependent on the identification of the optimal processing parameters for the local conditions.

With regards to Weld Metal and Consumables, the following conclusions were arrived.

1. Wet welds that satisfy AWS D3.6 Specification Type B Classification are readily achievable for depths less than 200 ft. and for steels with carbon equivalent less that

0.40 wt. pct. For depths less than 100 ft., presently available consumables are capable of producing consistent results. Between 100 and 200 ft., some variations in weld behavior (chemical composition, electrode operability, porosity, etc.) are sometimes observed.

2. Between 200 and 325 ft. water depth, repeatability in producing welds that meet AWS D3.6 Type B acceptance criteria becomes difficult.

Concerning future development, the Working Group recognizes that if the aim is to develop suitable and acceptable solutions for underwater welding in a predictable future, a number of preliminary conditions must be fulfilled.

1. The need to depart from traditional approaches and to "break circle".
2. The need to recognize that consumables most probably will have to be differentiated according to depth, possibly according to root, fill and/or capping functions.
3. In view of the highly challenging problems that are faced, all possible, even uncommon, designs and incident technologies at hand should be integrated in the development process.
4. In view of the multiplicity of factors involved in the design/formulations, development and evaluation processes, only a comprehensive, multi-disciplinary and systematic, scientifically-oriented approach is likely to lead to real significant progress.

4.2 Research and Development Needs

The Working Group identified and prioritized the following Research and Development needs to further Underwater Wet Welding applications in Structural Marine Fabrication.

1. Steels with carbon equivalent less than 0.40 wt. Pct.:
    a) For depths less than 100 ft., Type A welds (instead of the currently accepted Type B welds), by reducing porosity, by improving ductility and impact toughness, should be targeted.
    b) For depths between 100 and 200 ft., Type B+ welds (instead of the currently accepted Type B welds), by reducing porosity, by improving ductility and impact toughness, should be targeted.

c) For depths between 200 and 325 ft., Type B welds (instead of the currently accepted Type B- welds), by reducing porosity, by improving ductility and impact toughness, should be targeted.

2. Steels with carbon equivalent between 0.40 and 0.46 wt. Pct.:

   a) There is a need for more detailed investigation with respect to porosity, inclusions, fissuring, alloying element segregation, and hydrogen control in the weld metal.

3. The use of electrodes with high oxygen potential has shown promising results in underwater wet welding and should be further investigated for optimal effect in balancing porosity with inclusions and hydrogen control.

4. Consumables should be developed for welding the new TMCP steels, in particular, to produce weld metals with toughness that matches those of the base metals.

5. Priority in further consumable develop should be focused on C-Mn-Si and C-Mn-Si-(Low Alloy) systems with microalloying elements such as titanium and boron.

6. The rutile-cellulosic (E6013 Type) and rutile (E7014 Type) slags are capable of delivering quality underwater wet welds. Further improvements of these systems, expected to result in high quality consumables which will achieve the weld quality proposed earlier, should be targeted. Flexibility in design could be achieved by using coated tubular cored electrodes.

7. The use of FCAW has great potentials in underwater wet welding. Developmental work in the design of consumables, wire feeder and power design, using a systems approach, is strongly recommended.

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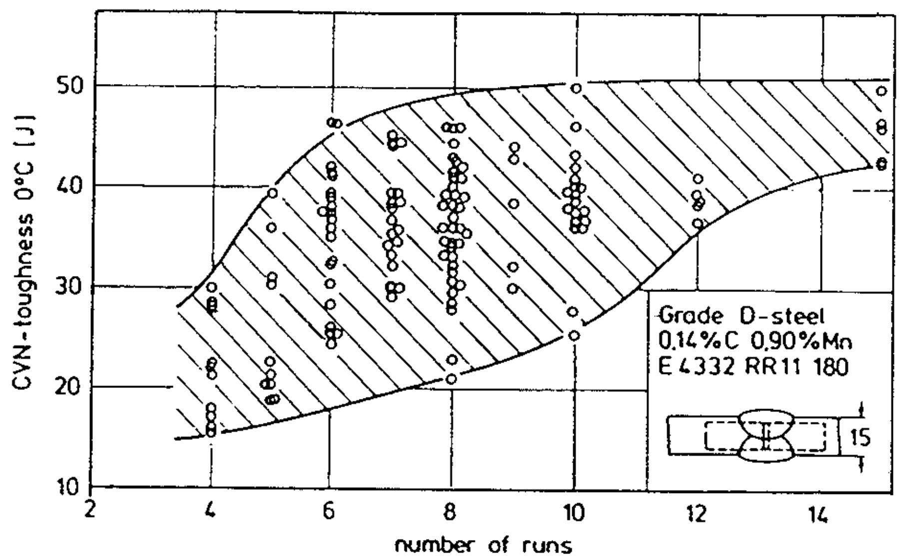

Figure 1. Weld impact toughness as a function of the number of runs in multiple pass underwater wet welding. (Hoffmeister and Küster, 1983)

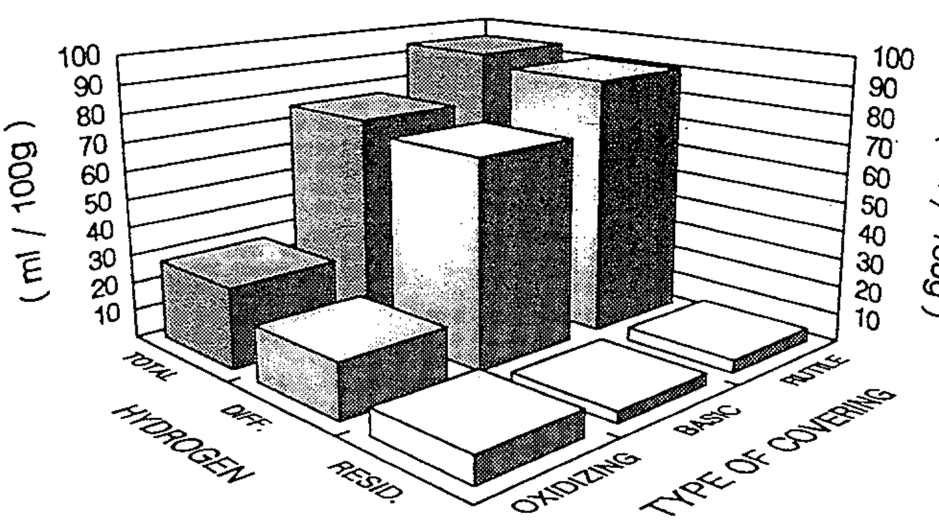

Figure 2. Hydrogen concentration in underwater wet welds as a function of the type of electrode coating. (Gooch, 1983)

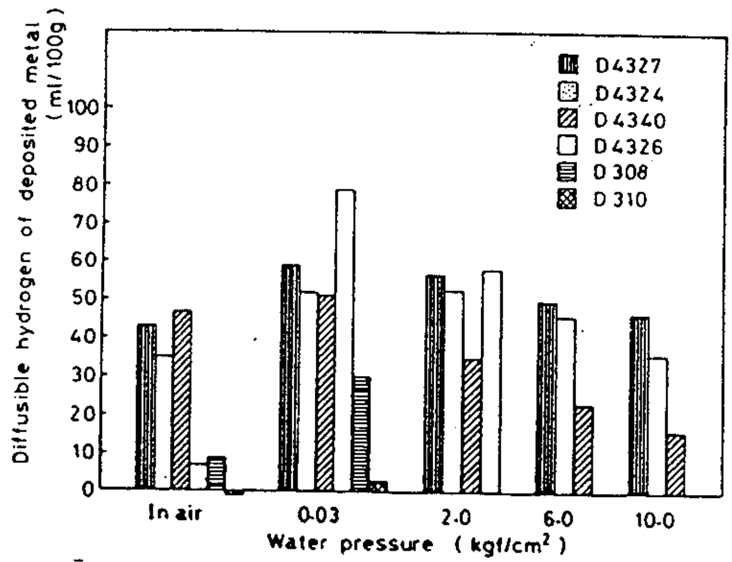

Figure 3. Relation between water pressure and diffusible hydrogen of deposited metals in underwater wet welding. (Ando and Asahina, 1983)

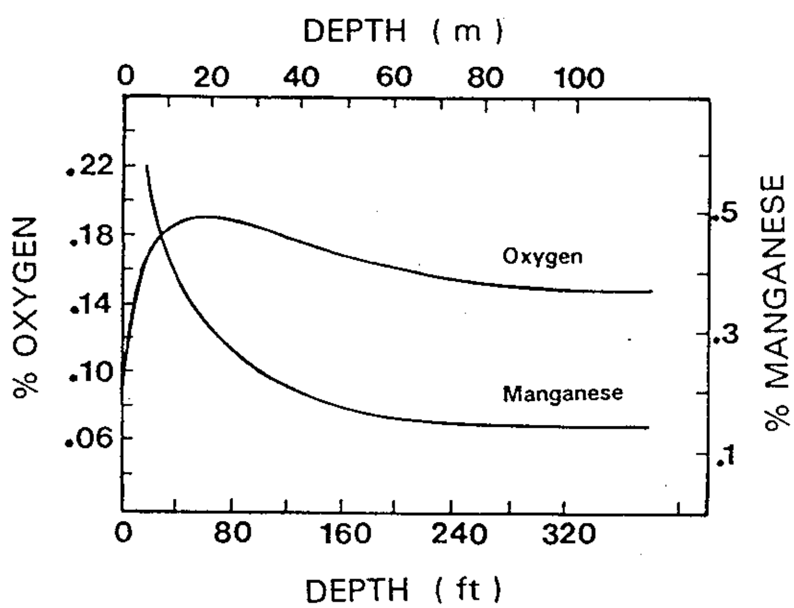

Figure 4. Underwater wet weld metal oxygen and manganese content as a function of water depth. (Ibarra and Olson, 1992)

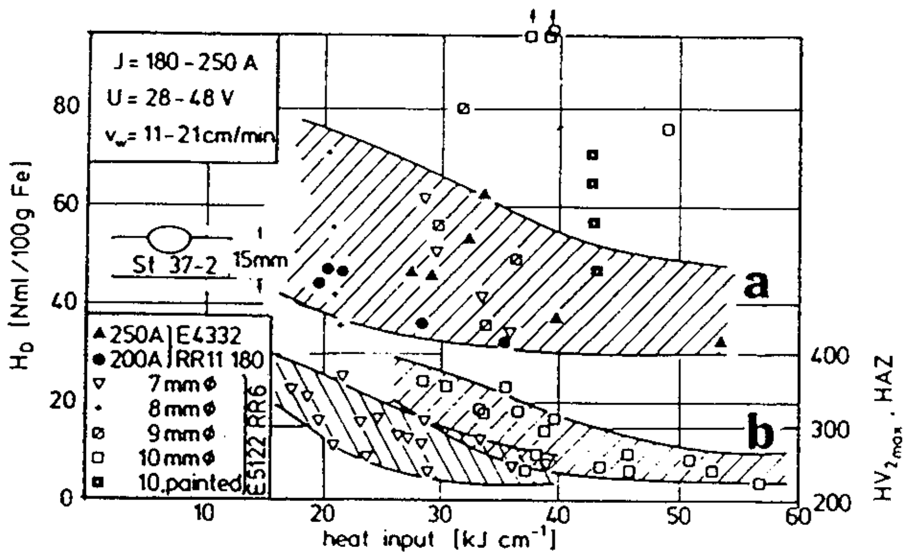

Figure 5. Effect of heat input on diffusible hydrogen content and heat affected zone hardness in underwater wet SMA welding. (Hoffmeister and Küster, 1983)

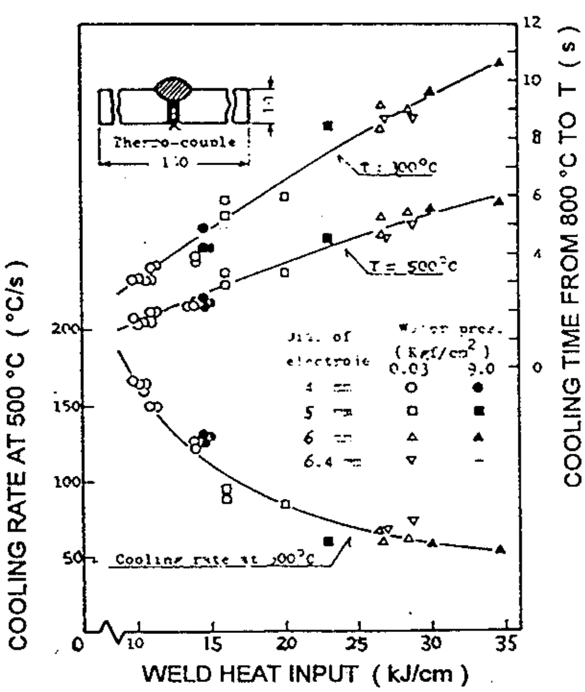

Figure 6. Effect of weld heat input on cooling rate and cooling time at fusion line in underwater wet welding. (Hasui and Suga, 1980)

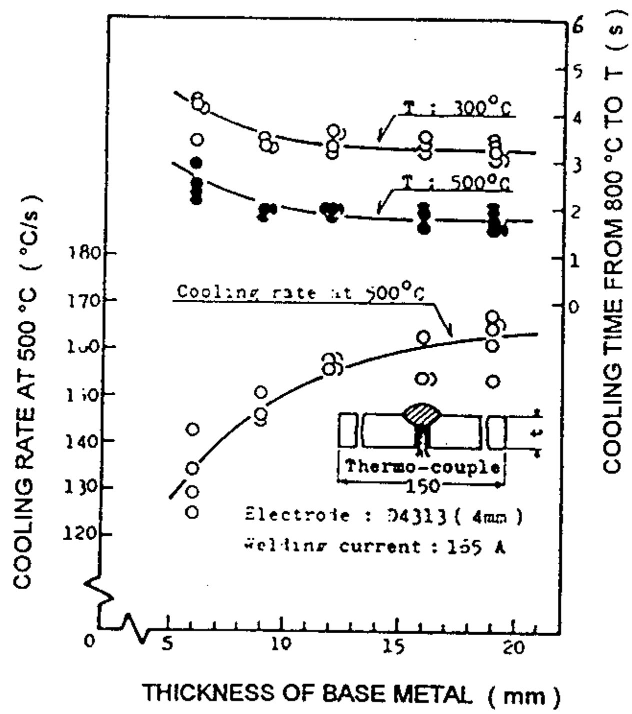

Figure 7. Effect of thickness of base metal on cooling rate and cooling time at fusion line in underwater wet welding. (Hasui and Suga, 1980)

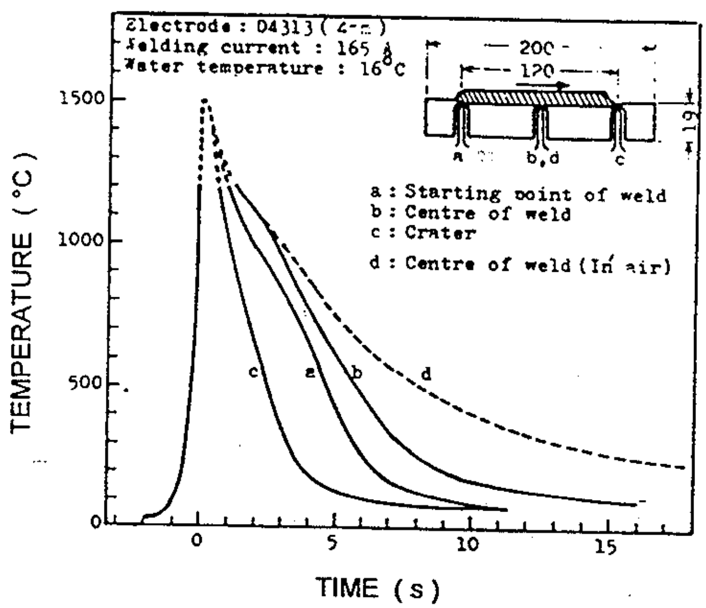

Figure 8. Temperature profiles of underwater wet welds at different positions along the weld. (Hasui and Suga, 1980)

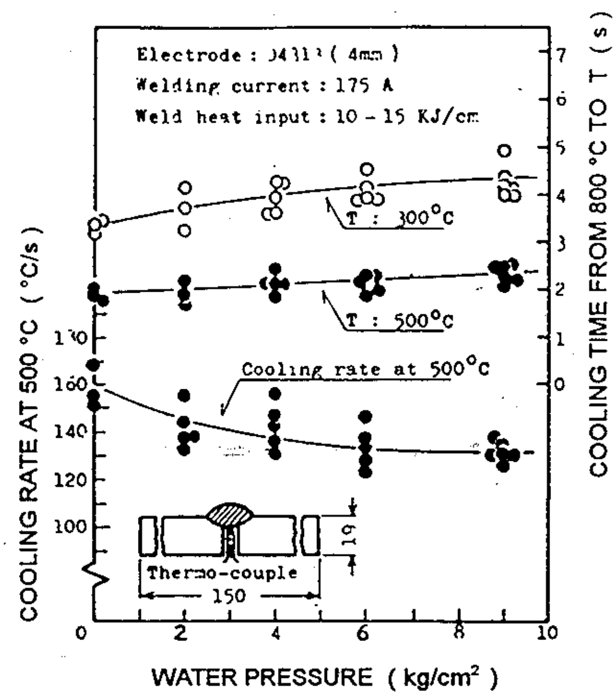

Figure 9. Effect of water pressure on cooling time and cooling rate at the fusion line in underwater wet welds. (Hasui and Suga)

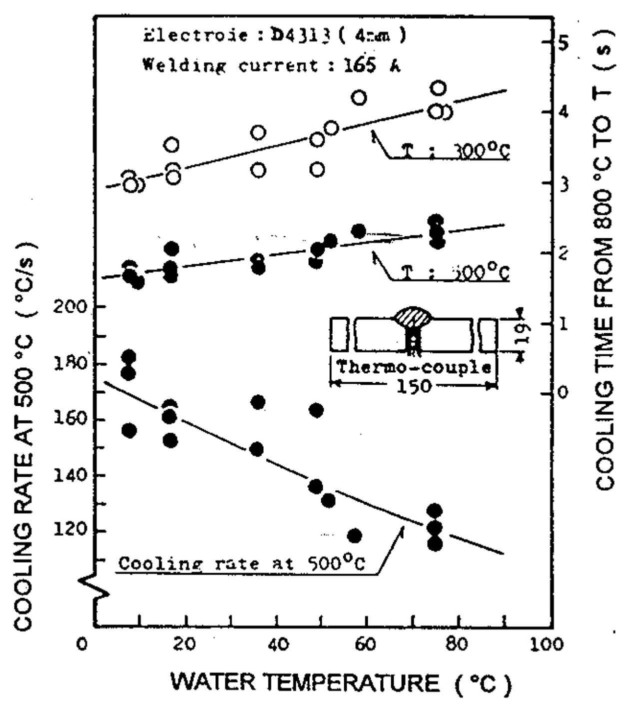

Figure 10. Effect of water temperature on cooling rate and cooling time at fusion line in underwater wet welds. (Hasui and Suga)

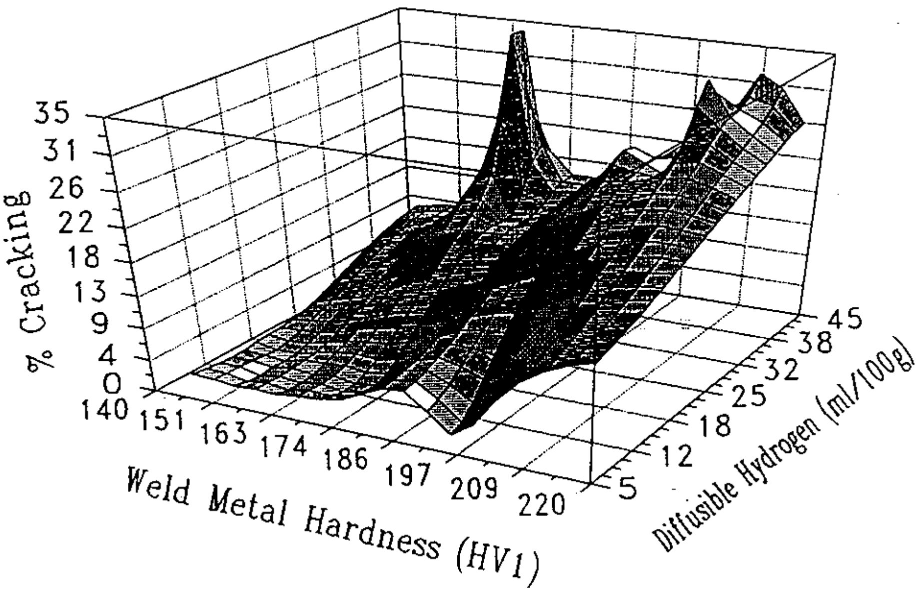

Figure 11. Cracking susceptibility as a function of weld metal hardness and diffusible hydrogen content of underwater wet welds. (Nóbrega, 1981)

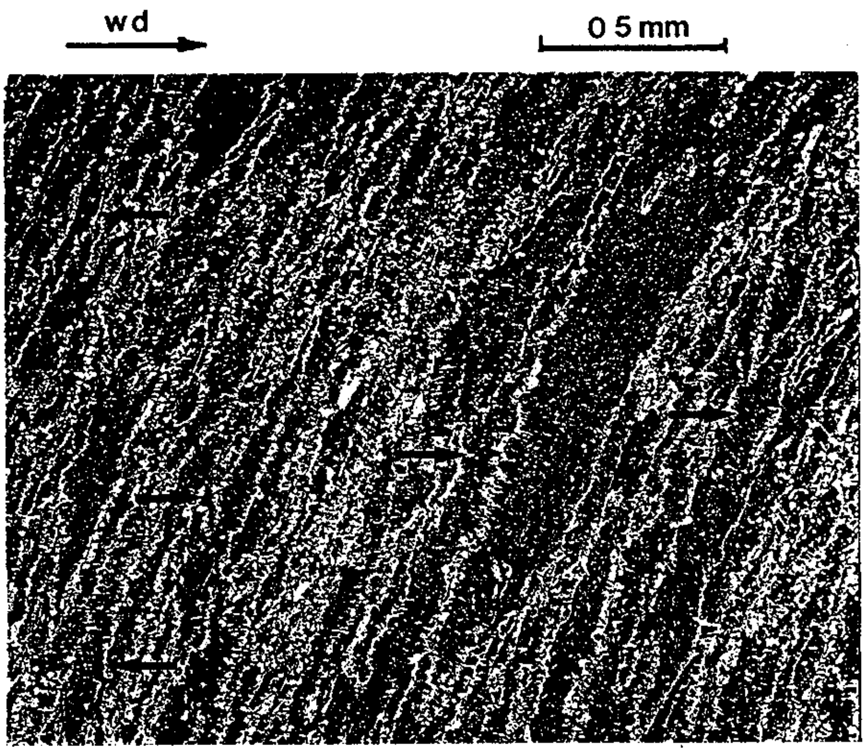

Figure 12. Longitudinal cross-section of an underwater wet weld deposited using a rutile electrode showing cracks that are aligned with the columnar grains. (Pope, 1994)

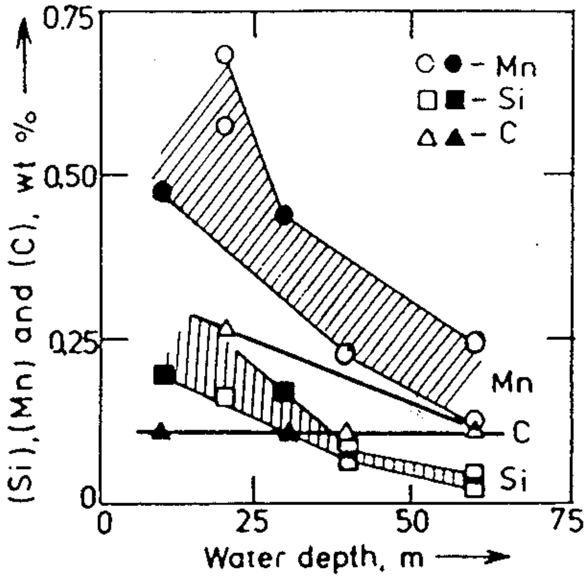

Figure 13. Variation of silicon, manganese and carbon concentration with water depth in underwater wet welds. (Christensen, 1983)

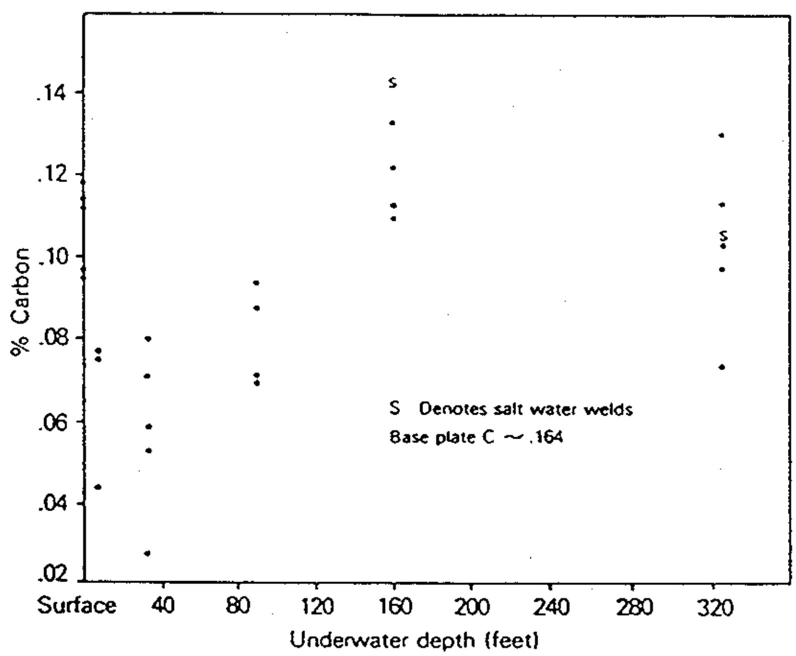

Figure 14. Carbon concentration as a function of water depth in underwater wet welds. (Ibarra, Grubbs and Olson, 1987)

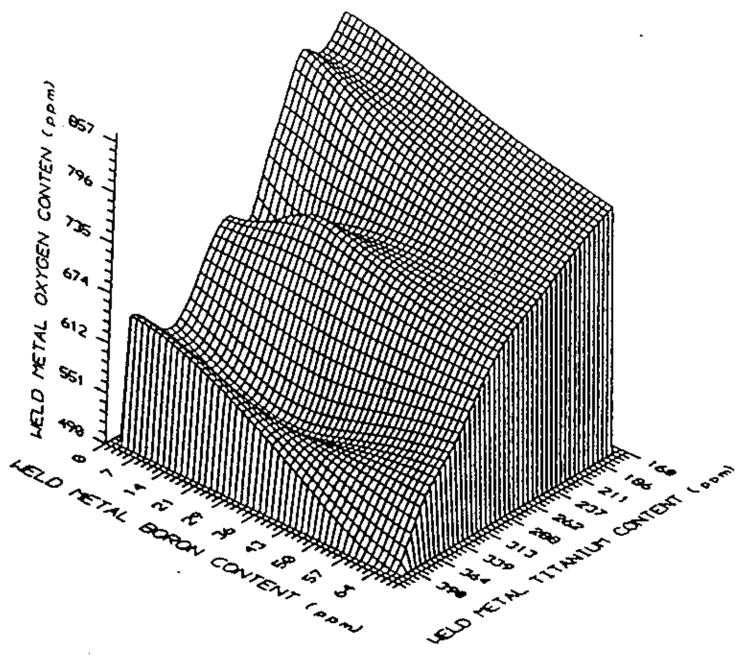

Figure 15. Underwater wet weld oxygen content as a function of titanium and boron concentration. (Sanchez-Osio, Liu, Olson and Ibarra, 1993)

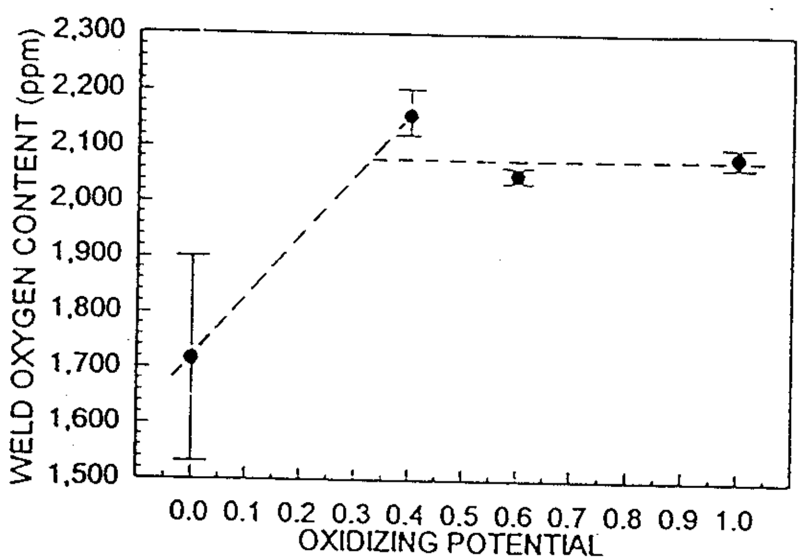

Figure 16. Variation of underwater wet weld oxygen concentration as a function of oxidizing potential of an electrode. (Pope, Liu and Olson, 1994)

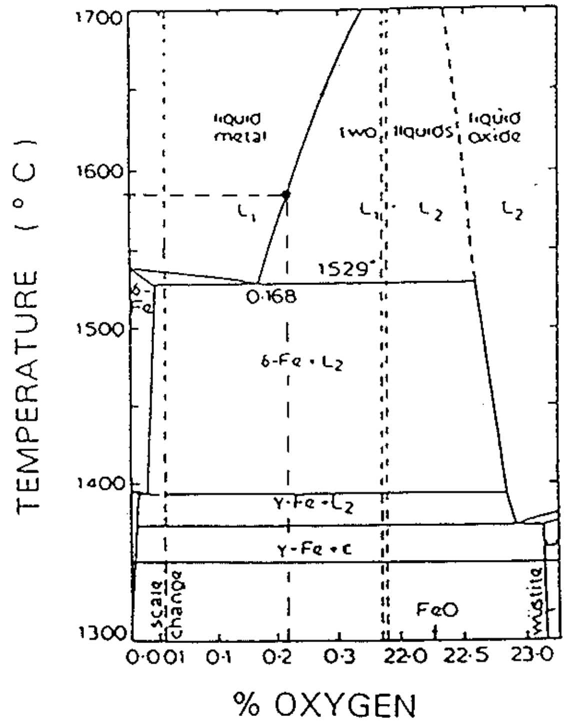

Figure 17. Equilibrium Fe-O phase diagram illustrating the region of two liquids, Fe(l) and FeO(l), that may be controlling the oxygen content of an underwater wet weld. (Van Vlack, 1977)

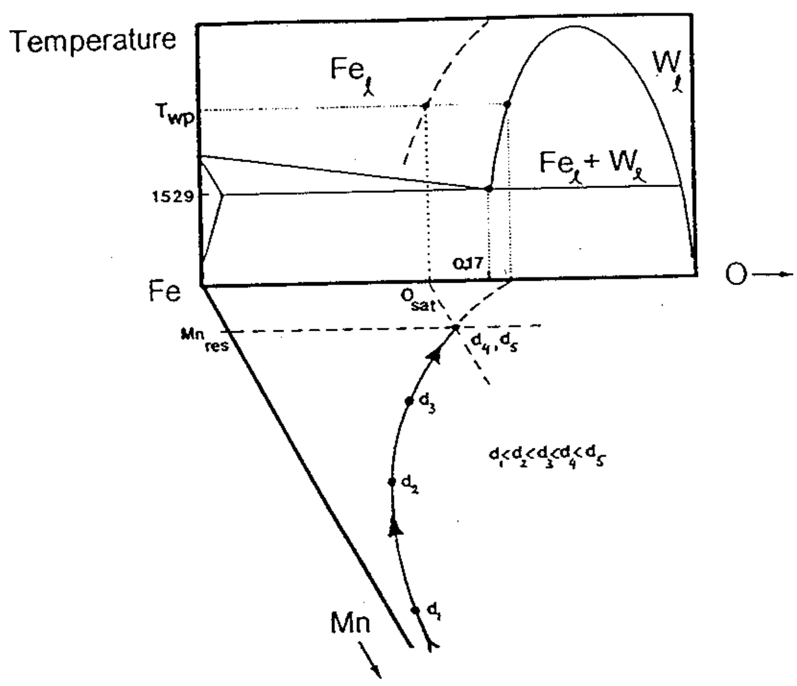

Figure 18. Complex variation of manganese and oxygen concentration as a function of depth (d_i). Notice the shift of the two liquid region boundary as a function of the deoxidizer. (Pope, 1994)

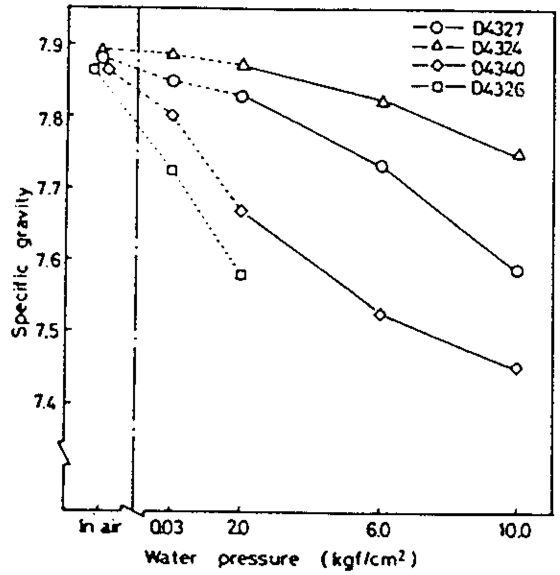

Figure 19. Relation between water pressure and specific gravity of underwater wet weld metals (Ando and Asahina, 1983).

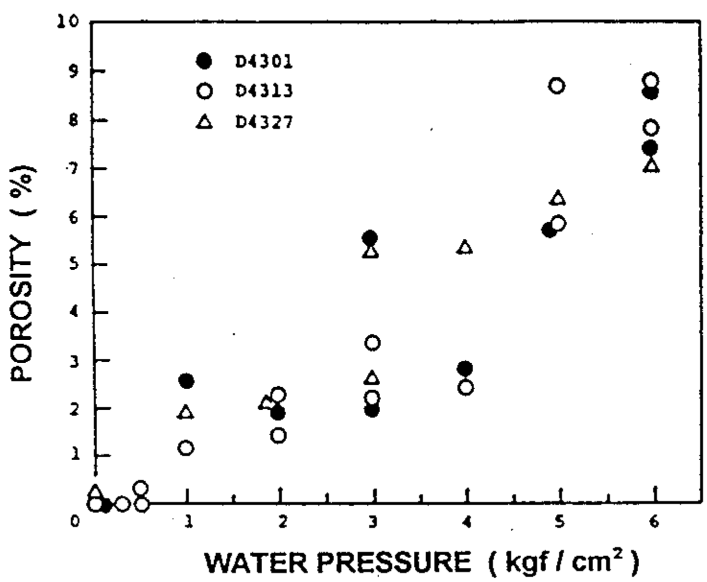

Figure 20. Underwater wet weld porosity as a function of water depth. (Suga and Hasui, 1986)

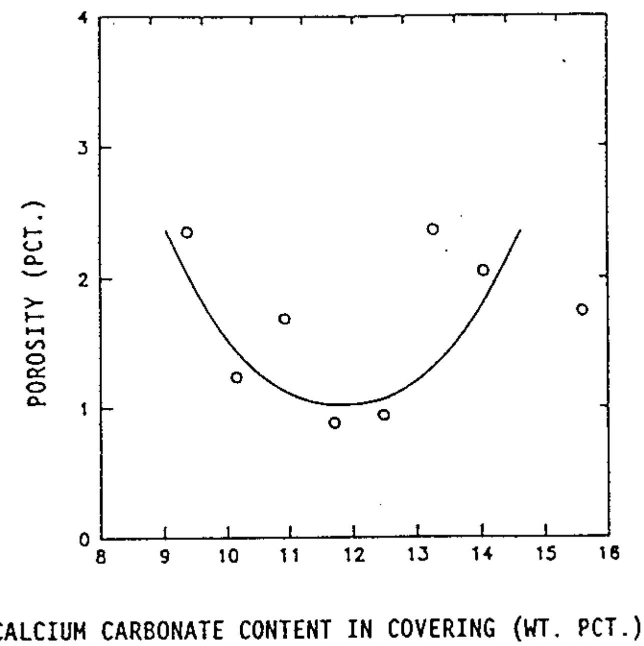

Figure 21. Effect of $CaCO_3$ additions on the porosity of welds made at 10 m of water depth (Sanchez-Osio, Liu and Olson, 1993).

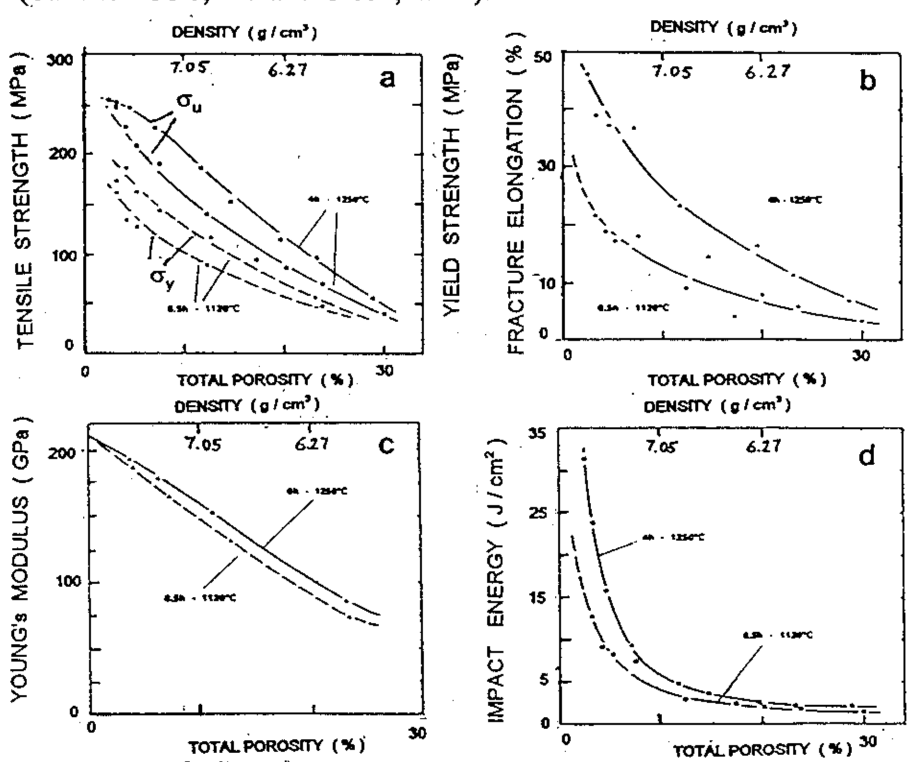

Figure 22. Effects of porosity on the mechanical properties of sintered iron (Danninger et al. 1993).

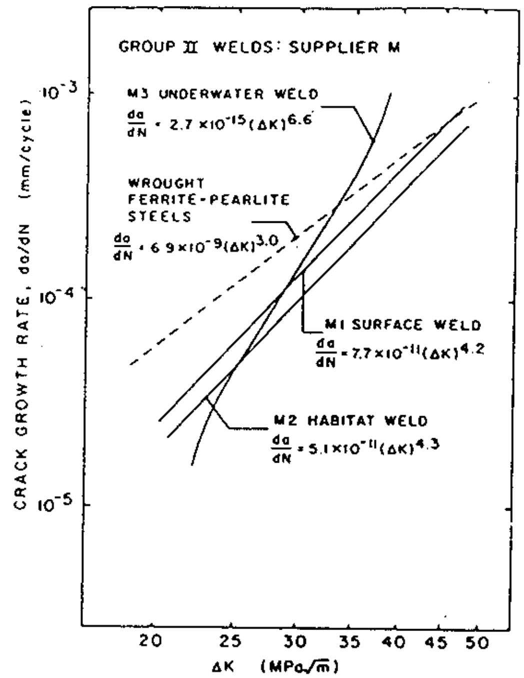

Figure 23. Fatigue crack growth characteristics of surface, habitat and underwater wet welds (Matlock et al., 1983).

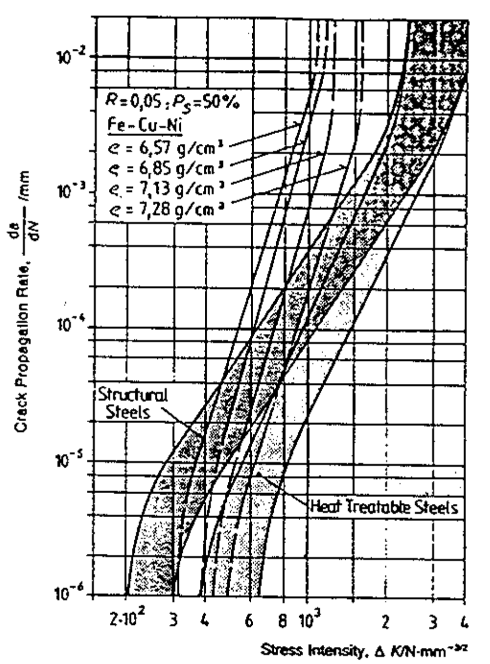

Figure 24. Crack propagation rate of wrought and sintered steels (Esper, Lenze, Sonsino, 1981).

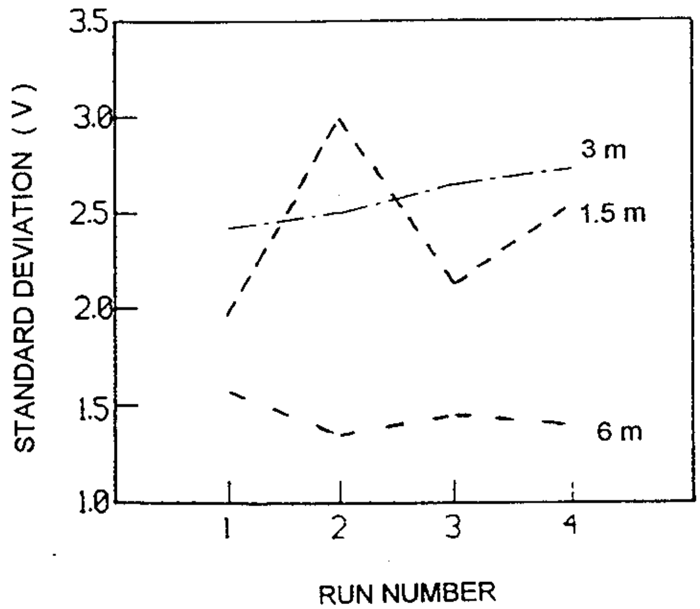

Figure 25. Arc stability measured in arc voltage (standard deviation) as a function of water depth. (Nixon and Graham, 1993)

CONSENSUS STANDARDS FOR DIVER-WELDER QUALIFICATION FOR UNDERWATER WELDING

Jack Couch	Oceaneering International
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ABSTRACT

This paper summarizes the present approaches of the qualification standards used to certify diver-welders in the field of underwater welding. Several areas are identified where improvements could be considered. In addition, prioritized recommendations of the Workshop on Consensus Standards For Diver-Welder Qualification are given.

INTRODUCTION

The ability to carry out underwater welding is multi-disciplined. Knowledge must be attained and skills must be mastered in the areas of diving, welding, and underwater welding. This multi-disciplined status of underwater welding has contributed to the development of numerous standards and specifications which set procedures and acceptance criteria for the process of personnel qualification. A partial listing of documents related to underwater activities is shown below; summaries are shown in Appendix A.

AWS D3.6-93, *Specification for Underwater Welding*

BSI 4515:1984, *Specification for Welding of Steel Pipelines on Land and Offshore*

Bureau Veritas, *Underwater Welding, General Information and Recommendation*, January 1986

Consensus Standards for Commercial Diving Operations, Association of Diving Contractors, Houston, TX

Det Norkse Veritas, *Recommended Practice RP B604*, January 1987

IIW Doc. S/C UW 124-90, *Standard Guidelines for Specification of Underwater Fusion Welding*

IMO Resolution A.536(13), *Code of Safety for Diving Systems*

MIL-STD-1692(YD), *Underwater Welding Requirements for Naval Facilities*

NAVSEA SO300-BB-MAN-010, *US Navy Underwater Cutting and Welding Manual*

NAVSEA Technical Manual, S9086-CH-STM-010, Chapter 074, Volume 1, *Welding and Allied Processes*, Section 6.30, *Underwater Welding*

NAVSHIPS 0994-LP-001-9010, *U.S. Navy Diving Manual*

NOAA Diving Manual, U.S. Department of Commerce

OSHA Commercial Diving Regulations, 29 CFR, Part 1910, Subpart T

U.S. Coast Guard Commercial Diving Regulations, 46 CFR, Part 197, Subpart B

Some of these documents are structured in a quite independent manner, not acknowledging another related standard. Others liberally reference related standards, and a few use another standard as a base document while listing special procedures and requirements particular to the specific activity pertinent to the document. For example, NAVSEA Technical Manual, Chapter 074, Section 6.30, *Underwater Welding*, identifies AWS D3.6-93, *Specification for Underwater Welding* as a base standard for wet welding performance qualification, while listing about four broad additions and about six exceptions that are related to specific concerns held by the US Navy.

Also standards that address the performance requirements related to diving generally do not contain information about the welding aspects. For example, the ADC document lists only five requirements related to welding, and all address only diver safety issues.

A consequence of the development of standards in the above manner is that underwater welding companies which typically support work under different regulatory agencies or in different areas of the world must qualify their personnel to different procedures and acceptance criteria. This can lead to an inflexibility for companies to carry out work and can lead to seemingly redundant expense related to personnel qualification.

APPROACH TO QUALIFICATION

Most of the welding standards deal with performance testing and acceptance criteria. Very few include prequalification criteria, such as training and previous experience necessary to develop the skills that are being tested.

By contrast, the diving standards, such as the ADC document and the US Navy Diving Manual, contain much detail including a position hierarchy and a rigorous qualification/experience format for the progression from diving tender to diver to diving supervisor (ADC system) or from second class diver to first class diver to master diver (USN system).

These differing approaches are probably a result of the type of end product. An underwater welder produces a finished weldment that is inspected as a part of the acceptance process. A diver provides a service underwater, the successful delivery of which is the acceptance process. Due to a more intangible service, diver qualifications have focused on prequalification steps, such as training and as experience at less difficult tasks, and have included as well as the more common performance testing. These differing qualification processes are analogous to the concepts of quality control and quality assurance. In very general terms, quality control approach has relied upon inspecting quality into a product, while the evolved quality assurance approach takes precautions to ensure that things are done right the first time.

This is not to say that underwater welders do not go through proper training and prequalification, but only that the qualification standards either do not address or certainly do not emphasize these components of qualification. Training and experience seem more the jurisdiction of the employing company or agency.

SUGGESTED AREAS FOR IMPROVEMENT

As can be concluded from the above discussion, there are several areas where the qualification process for underwater welders could be improved to the benefit of the employer and the employee. These areas are not unique and can be found in more than one of the common underwater welding standards.

1. Required training for underwater welders:
   Should training be a mandatory part of underwater welding certification?
   Diving companies do carry out training of diver-welders to the degree necessary to achieve satisfactory performance on qualification testing. The level of training is commensurate with the difficulty of the welding task and with the expense involved with the qualification testing. For example, dry welding at shallow depths (less than 15 feet) does not necessitate more training than that needed for surface welding qualification. But, qualification of hyperbaric welding at great depths (about 500 feet) is very expensive, thus the diving company employs training and prequalification, and uses experience as an indicator of success in passing the qualification test. The economics of the performance qualification testing is a factor in the level of preparation necessary for the diver-welder.

2. Prequalification as an surface welder for similar welding processes:
   Should prequalification, in the form of training and experience, be required as part of the process?
   It is believed that all diving companies do in fact choose to prequalify diver-welders to surface welding codes such as AWS D1.1 or API 1104. This serves as a basis for welding underwater. Most underwater welding code, however, do not require the prerequisite.

3. Required minimum experience with less difficult tasks involving underwater welding:
   Is there a valid basis for accruing experience fillet welding before permitting groove welding? What about out-of-position welding?
   Although not recognized in the codes, this probably happens in practice, again due to economics. Inexperienced welders that can pass out-of-position welding tests generally show lower productivity for this type of welding, so are assigned easier welding tasks to increase their experience and the level of their confidence; later they move on to the more difficult welding.

4. Prequalification in underwater NDT:
   The performance of underwater diver-welders should be viewed in accordance with the QA concept, do it right the first time. As such, training, experience and qualifications "outside" the traditional minimum to "lay a satisfactory weld" should be given due consideration. Welder-divers should be capable to recognize and correct imperfections (eg. by grinding) during the welding and prior to the final inspection. In this respect it is valuable to have diver-welders trained and qualified in underwater NDT. Furthermore, practical realities of deep water hyperbaric welding can have the welder assisting a top-side inspector with the required NDT (here again economics is an important factor). Similar situations can arise for wet welding.

5. Unified qualification maintenance periods:
What is the limit on the duration of the certification? What should be the parameters?
Unlike surface welders, diver-welders are rarely fully employed by underwater welding tasks due to the nature of the business. During slower periods they are employed for cutting, rigging and other diver jobs. Underwater welding skills (particularly wet welding skills) will deteriorate with lack of use. Renewal of certification is necessary to reaffirm the skill level, and generally after an appropriate period of practice welding.

6. Diver requirements in underwater welding standards
Should a document that unifies diver and welder qualifications be developed? What are the dual certification parameters? Specifically, how do they interact?
This is not done in commercial underwater welding codes, but is mentioned for discussion purposes. In fact, commercial codes can carry disclaimers regarding diving and diving safety issues. Several reasons are given for keeping distinct standards: threat of post-accident litigation, little cross-expertise for the development of unified standards, tracking changes to governmental regulations, redundancy to existing diving standards, creating a cumbersome standards, etc. But, the subject is raised for discussion.

7. Certification by a single agency:
This would simplify the process, but who does the certification? The employer? An independent agency? An administration?
The American Welding Society has a program for performance qualification and tracking of surface welders. Would a similar effort be appropriate for underwater welders?

8. Contingency tests:
Are adjustment, confirmation or contingency tests necessary? Under what specific conditions?
Confirmation test welds evaluate the entire welding system at the worksite for production welding to demonstrate the correctness and appropriateness of the previous qualification (procedure and performance) and to indicate suitability of the chosen equipment in the specific work environment.

9. Agreement upon existing performance testing details:
Most underwater welder performance testing follows the methodology for surface welding, yet many include unique or specific tests. Should a more unified approach be adopted?

10. Needed essential variables:
Underwater welder performance qualification may be carried out in a dive tank, so does not necessarily test the diver-welder skills under actual site conditions. Variables that are not likely to be addressed with a dive tank qualification are: diver support, current, temperature, water turbidity, differential lighting conditions, and other visual parameters. However, often the test tank will provide a more severe environment than the offshore worksite. For example, the test tanks fresh water makes welding more difficult, the water can be turbid due to poor filtration, and the steel shell can have magnetic effects. Even when testing is carried out at the actual worksite the above parameters may be less severe than those encountered during the production welding due to local periodic effects, current, etc. Further, diver qualification standards do not address the above underwater welding skills.

11. Customer specifications:
It is believed that the consensus standards are treated as a minimum level of performance qualification by many customers, who add testing and other extras. These should be discussed as to whether they are candidates to expand the consensus standards.

12. Underwater fitup of joints:
Poor fitup is reported as a problem by diving companies. This task is generally assigned to a diver rather than a diver-welder for economic reasons. Underwater welding and diving standards do not have specific guidance or requirements for this type of work.

RECOMMENDATIONS

The following recommendations were developed and prioritized by the Workshop on Consensus Standards For Diver-Welder Qualification. These represent prioritized needs as seen by the industry and regulators.

AA. Third Party Certification for Wet Welders:
Under current certification schemes, the contractor is responsible to certify welders. Entrance into the market of companies with more expertise in diving than in wet underwater welding has led to concern that welder certification may not have been correctly carried out, and that as a result the overall quality of the industry may be compromised. It is recommended that a third-party certification scheme be implemented by the industry.

BB. Supplementary Evidence of Training and Experience:
Underwater welding codes and standards should be modified to include training and experience as a basis for certification in addition to the typical performance testing. Adequate training and experience are essential to the capability to consistently perform wet welding with quality results. The means as to how this is achieved is left to the code-making organizations, however, a specifically detailed and tightly structured scheme is not recommended to be included in a code.

CC. Prequalification to Similar Surface Welding:
The codes do not require prequalification, however, in many cases underwater welding is similar to surface welding. It is recommended that code-making organizations consider prequalification for underwater welding that is similar to surface welding, such as dry hyperbaric.

DD. Consider Effects of Restraint:
Many codes do not take into account that the effects of welding restraint can be greater under production wet welding conditions as compared with the conditions used for welder qualification. This is due in part to different cooling rates in production welds that are permitted by the code qualification thickness ranges, and in part by the greater structural restraint inherent to a repair situation that cannot be represented by welding a test plate. It is recommended that code-making organizations consider the aspects of restraint.

EE. Maintain Separate Standards for Welding, Diving and Nondestructive Testing:
The concept of a unified standard was not supported due in part to the distinct expertise for the various disciplines and in part to the existence of separate

organizations which presently maintain the standards. It is suggested, however, that the separate groups maintain a close liaison.

FF. Develop Guidelines for Damage Inspection and Repair:
Although strictly not within the mandate of the work group, this item was identified as one where the industry is in need of improvement. It is recommended to various code-making organizations to consider the development of a comprehensive document that can be used to organize, mobilize, and carry-out repairs to structures; with emphasis on pre-inspection, assessment, standard solutions, and follow-up.

GG. Safety Issues should be Addressed:
Many industry codes have not addressed safety issues, presumably for reasons of potential liability. The work group recommends that a means to accommodate significant safety issues be considered. Simple reference to safety documents is not considered acceptable, in that these documents can be lacking in the safety issues specific to the activity of underwater welding.

CONCLUSION

The standards for personnel qualification of diver-welders have developed regionally or to address the perceived needs of a particular agency or industry segment. These differing requirements should be resolved to promote more unified standards. Several areas are identified and recommendations given where existing requirements could be considered for more widespread use to improve control of the end product. In addition, several suggestions are made for improvements in the usability of the standards, and for the improvement of the industry at-large.

APPENDIX A
SUMMARY OF STANDARDS

DIVING STANDARDS

Consensus Standards for Commercial Diving Operations, Association of Diving Contractors, Houston, TX:
This standard addresses commercial diving operations and contains detailed requirements for the qualification of personnel. Formal schooling is necessary. Prequalification emphasizes actual work experience at lower work designations so tends to promote an apprenticeship approach. Other than five safety issues, underwater welding and cutting are not addressed.

IMO Resolution A.536(13), *Code of Safety for Diving Systems*:
This code sets recommendations for the design, construction and survey of diving systems, defined as diving bells, surface compression chambers, supporting systems, and handling systems. It does not relate to the qualification of divers, or to underwater cutting or welding.

NAVSHIPS 0994-LP-001-9010, *U.S. Navy Diving Manual*:
This manual provides information and guidance regarding the various types of diving activities undertaken by the US Navy. Appendix E address prequalification, training and qualification of personnel. Six grades of divers are defined, each with its own requirements. In general the higher grades build upon the successful qualification and experience of a lower grade. The system is quite detailed and complete. The five advanced grades require knowledge and experience with underwater cutting; underwater welding is not addressed.

OSHA Commercial Diving Regulations, 29 CFR, Part 1910, Subpart T
These regulations address commercial (non-governmental, non-scientific, non-instructional, non-rescue) diving activities in USA waters. Diving operations, procedures and safety issues for surface-supplied diving and for free diving are included. Requirements, but without certification details, for diver qualification are listed, including experience or training with the use of tools for assigned tasks. Safety requirements for underwater welding and cutting are listed.

U.S. Coast Guard Commercial Diving Regulations, 46 CFR, Part 197, Subpart B:
This standard sets requirements for the design, construction and use of vessels, systems and equipment that support commercial (non-governmental, non-scientific, non-instructional, non-rescue) diving operations in waters under the jurisdiction of the USCG. It does not relate to the qualification of divers, or to underwater cutting or welding.

WELDING STANDARDS

AWS D3.6-93, *Specification for Underwater Welding*:
This specification generally follows the AWS approach for welder qualification. Fifteen essential variables are listed, including five that are directly related to the underwater environment experienced by the welder-diver. Inspection and testing are specific to the class of welding carried out. Noteworthy is the period of effectiveness for qualified welders using specific welding procedures. Training and prequalification are not

referenced or required. Most detailed and complete document for underwater welding qualification.

BSI 4515:1984, *Specification for Welding of Steel Pipelines on Land and Offshore*:
This specification contains qualifications and requirements for pipeline welding. The Appendix J addresses hyperbaric welding with a limited section on welder qualification; a prerequisite of atmospheric welding is included, along with a recommendation of training for welding at pressure. Diving safety is by reference to *Diving Operations at Work Regulations,* 1981, No. 399, a UK DoE (now HSE) regulation.

Bureau Veritas, *Underwater Welding, General Information and Recommendation*, January 1986:
This document provides only general information, guidance and recommendations concerning various modes of underwater welding; no details as to qualifications and usage limits are given. Notable is that welder performance qualifications be carried out every year, and that adjustment tests and production tests be carried out for important welding. Formal training of underwater welders is acknowledged, but is not required. No specifics regarding diver qualifications are included.

Det Norkse Veritas, *Recommended Practice RP B604*, January 1987:
This document gives recommendations for underwater welding, including procedure and welder qualification. In general, the focus is more on dry welding methods. Welder qualifications are addressed including a prerequisite of qualification in similar procedures under atmospheric (and dry) conditions. The period for inactivity is six months. No qualification recommendations are stated for divers.

IIW Doc. S/C UW 124-90, *Standard Guidelines for Specification of Underwater Fusion Welding*
This guideline contains recommendations for scope and content (listings of items that should be considered) for specifications dealing with underwater welding. Noteworthy are prerequisite items dealing with training, and prequalifications.

MIL-STD-1692(YD), *Underwater Welding Requirements for Naval Facilities:*
This standard contains procedure qualification requirements and general guidance for underwater welding, with particular emphasis on shielded metal arc welding. Welder qualification is very basic, essentially only making reference to AWS D1.1, Section 5.

NAVSEA SO300-BB-MAN-010, *US Navy Underwater Cutting and Welding Manual*
This manual contains very detailed instruction for carrying out underwater cutting and welding. Numerous safety issues are addressed. Training and prequalification are only briefly noted.

NAVSEA Technical Manual, S9086-CH-STM-010, Chapter 074, Volume 1, *Welding and Allied Processes*, Section 6.30, *Underwater Welding*:
This manual cover a broad range of subjects; procedure qualification, performance prequalification, qualification and maintenance, production welding, inspection, monitoring and quality assurance, but is limited to the shielded metal arc process. The basis documents for dry welding qualification are MIL-STD-1689 and MIL-STD-248; and for wet welding qualification is AWS D3.6-93, although with numerous modifications. Training for welding and for underwater NDT (wet welding only) are required. Also included are confirmation tests (adjustment tests), and initial production tests. Diver qualification is by reference and without stated minimum level.

UNDERWATER WELDING PROCESSES, MECHANIZED AND AUTOMATED SYSTEMS

Rapporteur: **Dr. Jorge F. dos Santos,**

GKSS Forschungszentrum Geesthacht GmbH

INTRODUCTION

Operation of pipelines and other offshore installations would not be possible without on-site installation, repair and exchange procedures. Welding procedures carried out in hyperbaric dry environments are the most favoured procedures to perform such tasks since in this way the achieved mechanical properties comply with the applicable code requirements. Dry hyperbaric welding operations could be classified in two distinct groups according to the working depth: manned operations (down to approximately 360msw) and diverless operations.

In manual underwater welding operations the Shielded Metal Arc Welding (SMAW) and the Gas Tungsten Arc Welding (GTAW) processes are normally applied where qualified and highly experienced welder-divers are employed [1]. The processes, consumables and procedures employed in manual underwater welding operations have remained basically unchanged since the beginning of the eighties. No attempts have being made in the last two decades to use semi-automatic procedures (based on the Gas Metal Arc Welding - GMAW - process) offshore.

In order to reduce human intervention in such hostile environments and to improve weldment quality as well as reproducibility of qualified welding procedures, great emphasis has been placed on mechanisation in underwater welding. As a matter of fact, in the last two decades R&D activities have been taking place in various countries, aiming at the reduction of the work load on the diver through process mechanization. Currently three different orbital welding systems applying the GTAW process are reported to have successfully welded tie-in joints in several offshore fields in varying water depths [2-4]. Recently a new orbital welding system has been made available based on a modular design which applies the GTAW process for the root and hot passes and the GMAW process for the filler and cap layers [5].

However, for much of the world, especially in the Gulf of Mexico and Brazil the best potential for major new oil and gas reserves lies beneath the deep waters of the continental slopes, or in other words, at depths below 450msw. Repair operations at water depths greater than 360m (the present limit for ambient pressure diving) can only be carried out by fully automatic systems, part of a diverless underwater working station.

The growing potential of hyperbaric welding associated with the recent developments in robotics for underwater work suggested a possible solution for a diver less repair station.

This study discusses aspects of welding processes emphasizing their use in conjunction with mechanized or fully automated systems for underwater repair and construction. In the first part of this work a brief review of the current information on welding processes operating under hyperbaric conditions is presented. This summary has been based on a study prepared by Crane and Richardson for the Sub-Committee "Underwater Welding" of the International Institute of Welding [6], complemented with recent data on deep water applications of welding processes.

The second and third chapters of this work are concerned with mechanized and fully automatic systems for underwater welding respectively. The block concerned with mechanized systems describes the main reasons behind their development, the currently available systems, their track record and their future in the offshore market. The chapter on diverless systems takes into account the requirements, the handling system available, the different concepts and repair approaches as well as the present development stage of this technology.

The last chapter of this report summarises the future research and development work required in the field of welding processes, mechanized and automated systems.

This work covers the application of welding processes and systems under **dry hyperbaric** conditions only. The applications in wet conditions are presented elsewhere in this volume.

WELDING PROCESSES

General Aspects

A large body of literature exists on the use of arc welding techniques in connection with offshore construction and repair [7-11]. The majority of publications consider the influence of environmental conditions on the behaviour of specific welding processes and/or the resultant influence on weld metal properties. Over the last twenty years considerable research effort has been expended to improve process performance and develop suitable control strategies for the various welding processes.

The influence of pressure on process performance and requirements is governed to a large extent by changes in arc properties. All arc processes involve the generation of an electrically conducting gaseous plasma. For welding purposes the arc must generally be self sustaining and provide a stable source of heat. The arc may be regarded as encompassing three regions; the non-equilibrium anode and cathode fall zone close to the respective electrode surfaces and the plasma column [12]. The fall zones are characterised by high current densities, high electric field strengths and the existence of large space charges (an excess of particles with a charge opposite to that of the electrode). These extend to a distance of about 10^{-6}m from the electrode surface. The remaining portion of the arc is the plasma column which (by definition) has no net space charge. It should be noted that these regions are not distinct but merge in a physically continuous manner.

The structure of the arc column is controlled by the material properties of the plasma, environmental conditions and the current which the arc must support. The equilibrium operating condition occurs when the rate of electrical energy supplied (voltage x current) is balanced by the energy losses to the electrode, workpiece and surrounding atmosphere (Fig. 1). Arc voltage may therefore be regarded as an indication of the total energy loss from the arc column (for a given welding current).

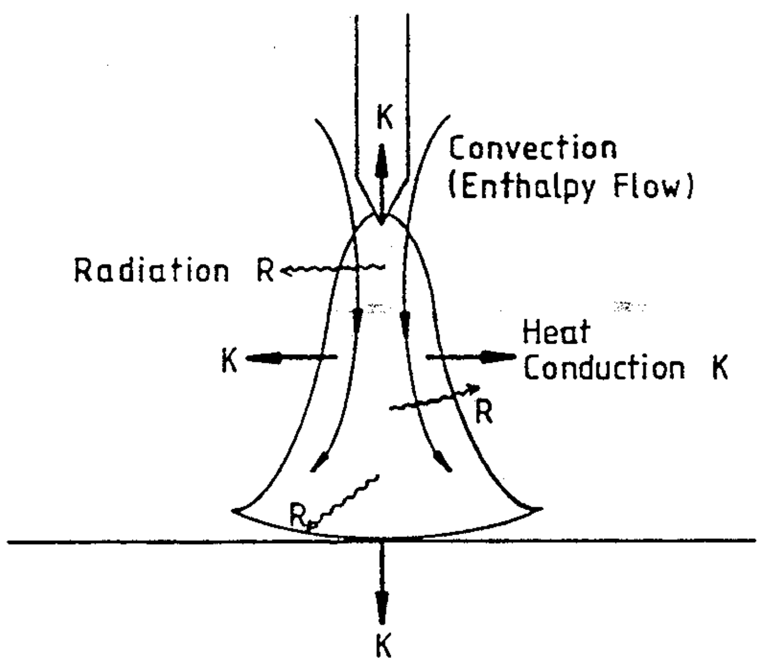


Figure 1 - Illustration of arc energy loss mechanisms.

As the ambient pressure is raised above one atmosphere the physical properties of the plasma are altered and particle densities increase in proportion to the absolute pressure. Thermal conductivity increases due to the rise in particle collision frequency causing greater energy losses from the outer regions of the arc. This in turn is reflected by a rise in arc voltage.

The increased thermal conductivity forces the arc to contract and adopt a new minimum energy loss configuration. The cross section of the conducting core is reduced resulting in a rise in column core temperature (and hence in electrical conductivity) to maintain the required current flow. The contraction of the arc core also results in an increased radiative energy loss which occurs as a result of a re-distribution of the arc energy (and may be inferred from the form of the enthalpy term in the energy balance equation [13]).

This general behaviour is common to all types of welding arcs presently used offshore. However, the results in terms of particular changes in arc behaviour depend on environmental conditions and are therefore process dependent.

Shielded Manual Arc Welding (SMAW)

Shielded manual arc welding is presently used for the majority of offshore manual welding applications. This process may operate either in the wet or in a dry environment. In the former case the arc is in direct contact with the water and relies on the coating constituent to prevent oxidation of the molten metal droplets. Wet welding is extensively used in the Mexican Gulf and elsewhere, presently gaining in importance also in the North Sea.

During SMA welding, an arc is ignited (by contact) between the workpiece and a flux coated consumable metal rod clamped in an insulated electrode holder. The coating decomposes on contact with the arc and performs a number of functions including shielding of the molten weld pool and metal droplets during transfer. The coating also supplies an excess quantity of easily ionisable material to the arc which substantially influences the energy balance behaviour. As a consequence, most authors [14-16] report that arc voltage is only slightly increased by a rise in ambient pressure. However, voltage fluctuations, due to increased metal droplet detachment frequency and column electric field strength, become more severe (Fig. 2) [15,16].

The SMAW process normally operates with a constant current steady state DC power source characteristic. Typical power source open circuit voltages are of the order 65 to 80V. Power is usually supplied from a surface based unit via long welding cables. Welds are made at depths of up to 150m in dry hyperbaric and wet environments [17,18]. The process relies to a large extent on the formulation of the electrode flux for chemical stabilisation and the skill of the welder-diver. As a result the tolerance to changes in power source dynamic behaviour is greater than that observed with other arc welding processes.

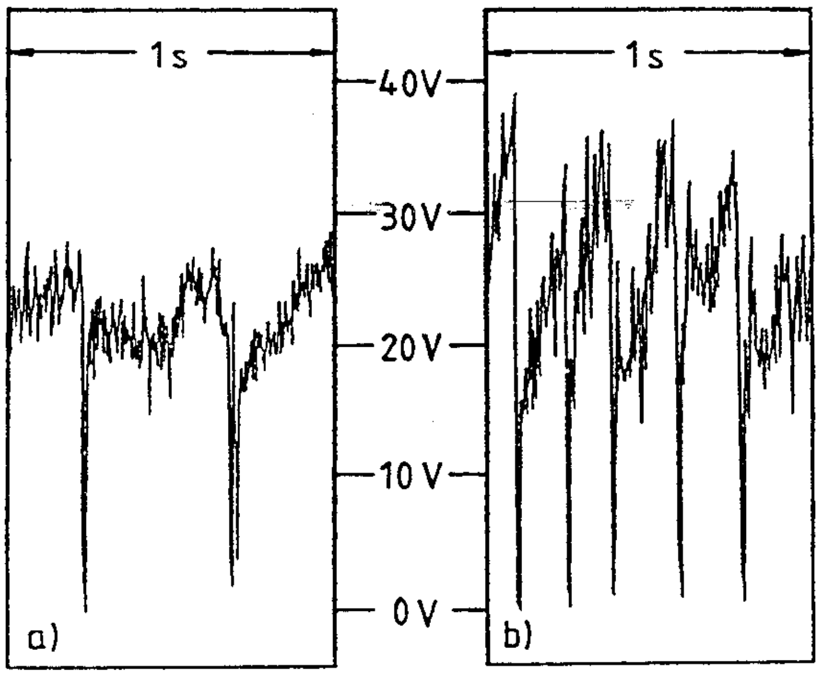


Figure 2 - Arc voltage fluctuations in SMAW at (a) atmospheric and (b) 150msw.

Gas Tungsten Arc Welding (GTAW)

The influence of pressure on the GTAW process has been studied extensively and several comprehensive descriptions of arc and process behaviour at elevated pressures have been published [19,20]. The GTA arc may be described as free burning ie, the discharge is not subject to external constraints other than those imposed by the electrode geometry and environmental conditions. Arcs of 1mm length or greater tend to be dominated by the inert gas supplied as a shield for the electrode and molten weld pool, arc characteristics are therefore subject to the physical properties of the shielding gas (shorter arcs may have a significant metal vapour content and electrical behaviour can deviate from that predicted for a gas dominated plasma).

In practice arc column voltage is observed to increase in proportion to the square root of absolute pressure (P) measured in bar (Fig. 3, [19]). This is indicated by an increase in the electric field strength (E) of the arc column. The total arc voltage may be approximated by the sum of the fall voltages (V_0) and the plasma column voltage ie,

$$V_{arc} = V_0 + K_1 I^{-1} + E_1 K_2 l (I \cdot P)^{0,5}$$

where K_1 and K_2 are constants, l the arc length and E_1 the one bar electric field strength. E_1 is of the order 0.8V/mm and 1.8V/mm for argon and helium respectively. At low currents the V/I gradient is negative (Fig. 4, the term K_1 dominates), buoyancy forces have a significant influence and arc stability is poor. The fall voltage (due to the non-equilibrium electrode regions) is found to be only weakly dependent on ambient pressure, deviations falling within the bounds of errors typically encountered during experimental measurements [19].

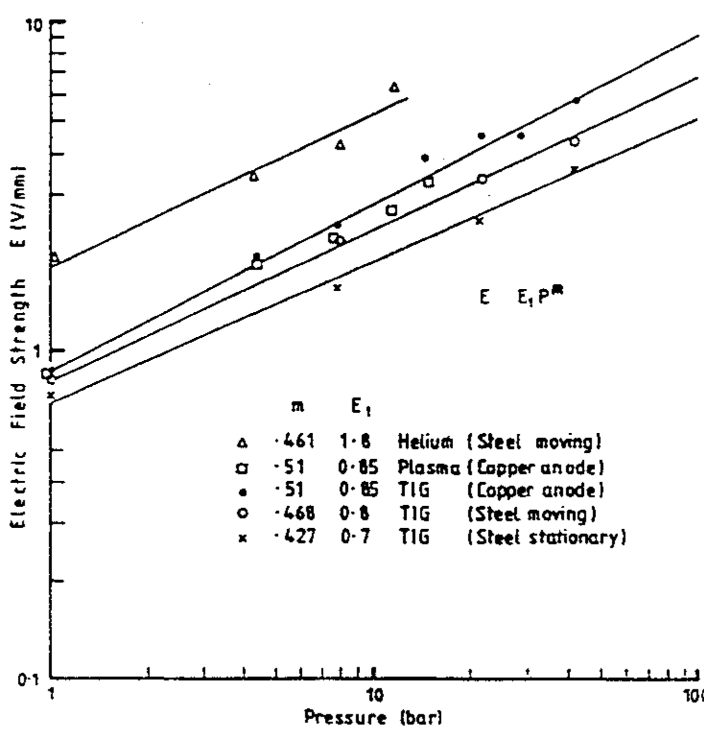


Figure 3 - The influence of pressure on arc column electric field strength.

As the working pressure increases, the arc voltage becomes increasingly less stable. Instabilities are thought to be generated in the region of gas entrainment close to the cathode. These may be due to buoyancy forces [21] in the hot non-current carrying layer of the arc immediately adjacent to the arc core. Allum et. al. [22] have shown that gas flow in the arc column is turbulent at pressures of only a few bar. This leads to unstable (stochastic and time dependent) energy losses and consequently to voltage fluctuations. The amplitudes of these oscillations increase with working depth due to the pressure dependence of the electric field strength.

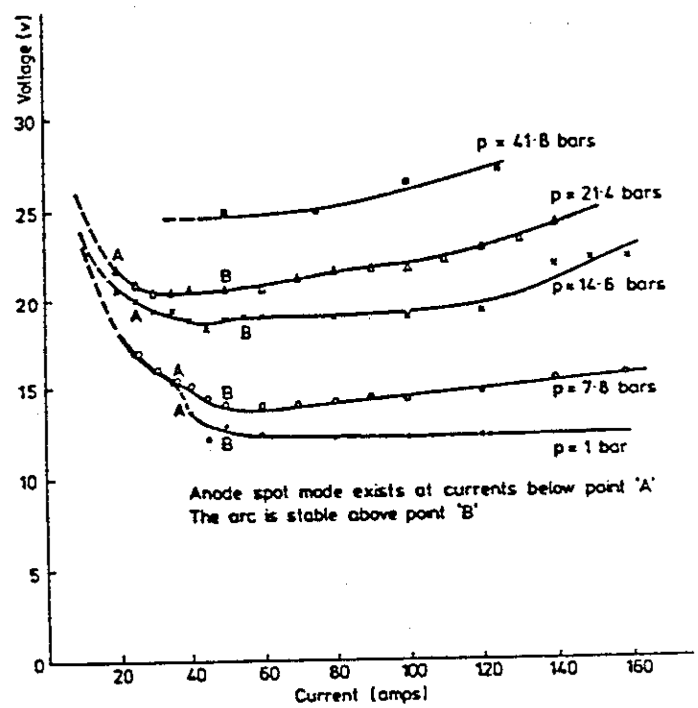


Figure 4 - Current characteristics of a 4mm argon GTA arc on a moving mild steel anode.

Magnetic field interactions with the arc plasma also act to destabilise the process. Arc blow, due to residual magnetism in the workpiece or interactions occurring as a result of the self induced fields in the arc and workpiece (associated with the current path through the workpiece) cause significant voltage disturbances [19] and amplitudes increase rapidly with increasing pressure.

The effects of ambient pressure and contamination by metal vapours on the arc characteristic has been recently investigated in a series of theoretical analysis [23-25]. The partial pressure of electrons in the arc plasma decreases proportionally with the reciprocal of the square root of the ambient pressure when there is no metal vapour contamination of the plasma. When contamination with metal vapours occur the electron density increases proportionally to the square root of the total number of the vaporized particles, since the ionization potential is lower compared to that of normal shielding gas such as argon or helium. The electron densities at relatively low temperatures are increased by selective ionization of vaporized metal elements and the amount of these is proportional to the square root of the contamination coefficient of the vaporized metal element at low temperature. The metal vapour is easily ionizable and therefore, vaporized metal elements will be fully ionized above 6000°K. This temperature depends on the ionization potential of the contaminated material and the contamination factor. The value of the partition function is also influenced by this phenomena [25].

Hyperbaric GTA welds are made with constant current power source output characteristics, typically with pulsed current waveforms. Applications include both manual and automated root and filler pass welds. Tolerance to process parameter variations during root welding procedures diminishes with increasing ambient pressure and accuracy becomes critically important at depths below 200m. In general fast response (dI/dt) power sources are required to facilitate pulse generation and to provide a degree of immunity to voltage transients thereby ensuring continuous arc operation with minimal variation in current levels. High duty cycles are required, particularly for deep water automated operations. Mean currents are typically of the order 80 to 150A with peak pulse levels of up to 300A for a duration of a few tens to a few hundred milliseconds.

The GTA process is presently qualified for repair operations to depths of up to 500m [2,26]. Beyond this limit it is unlikely in practice that process stability can be sufficiently maintained to meet the stringent tolerance requirements, although test welds at greater depths have been successfully accomplished.

Flux Cored & Gas Metal Arc Welding (FCAW/GMAW)

The Flux Cored Arc process has been used offshore for a number of years and is characterised by high deposition rates and high duty cycles (compared with SMAW). The flux may be formulated to improve arc and metal transfer stability and weld metal chemistry. However, flux constituents (generally) are not dominant in the arc column. Pressure therefore has a greater influence on process performance than in the case of the SMAW process. FCAW is typically applied to filler and capping pass welds (root welds are normally made with the GTAW process which offers greater control over bead shape and avoids the possibility of slag entrapment).

The Gas Metal Arc process has been studied in the laboratory by a number of research groups. Process stability must be maintained electrically [27] because, unlike the cored wires, the scope for stabilisation of the arc through chemical changes in wire composition is severely limited. The potential advantages of solid wire over cored wire operations include low cost consumable developments and higher duty cycles (slag free welds) with the possibility of near continuous automated operation. Stol Comex Seaway A/S has reported the use of solid wire GMAW for root pass welding applications although it is not known whether the process has been exploited offshore. Root and filler pass welds have been successfully produced in the laboratory using open arc pulsed current techniques (minimal short circuiting).

Both of these processes depend on control of the electrical input to stabilise the arc and metal droplet transfer. Control is maintained by operating with a sloping power source output characteristic which produces a self adjusting arc (Fig. 5).

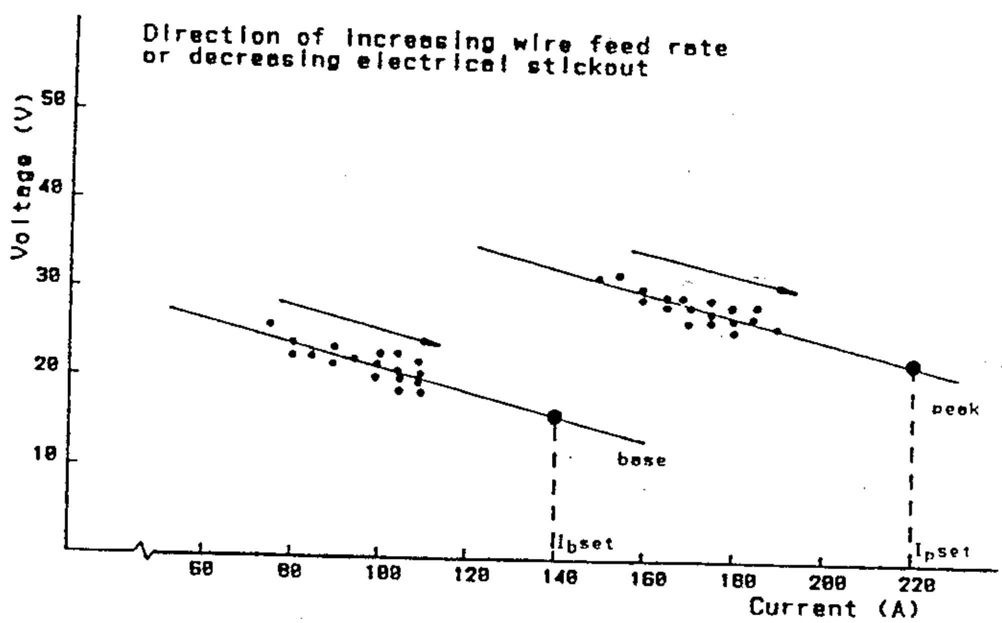


Figure 5 - Power source output characteristic for a self adjusting solid wire GMA weld at 30bar in argon.

Control may be understood in terms of the Halmoy burn off equation relating wire melting rate (W_b) to current (I) and electrical extension (l):

$$W_b = \alpha I + \beta l I^2$$

where α and β are constants (dependent on wire composition and size) and represent arc impingement and ohmic heating terms respectively.

Under equilibrium conditions wire feed rate and wire burn off rate are exactly matched. Any disturbance causing the arc to deviate from its equilibrium length causes a corresponding change in current (due to the associated voltage change) which influences the burn off rate and acts to restore equilibrium.

The optimum current variation (ΔI) required per unit change in arc length to restore equilibrium is a function of the wire composition and size only. However, because arc voltage is pressure dependent the slope of the power source output characteristic (k) must change with pressure approximately according to:

$$k = \frac{E_1 \, p^{0.5}}{\Delta I}$$

The dynamic behaviour of the power source also has a significant effect on process stability. If the response rate (dI/dt) is too low the current does not change sufficiently rapidly to maintain equilibrium and short circuiting or burn back occurs. If the response rate is too fast, the current tracks voltage transients causing large scale-oscillations, often resulting in arc extinction. This is a particular problem at high pressures where turbulent gas flows introduce noise on the arc signal. In general, power sources require high source voltages to minimise the statistical likelihood of arc extinctions due to large voltage transients.

During pulsed current operation the response rate between pulse levels is also significant. If the slew rate is too low the metal droplets fail to detach and globular transfer results. When the slew rate is high fine spatter is produced. This my be due to physical shock or gas pore explosions in the molten neck of the wire. Similar behaviour is observed with current pulses injected to clear short circuits and facilitate arc re-ignition.

Optimum response rates (for small diameter wires ≤1.2mm) are of the order 0.15 to 0.5 A/s. Operational envelopes for cored wires tend to be greater than for solid wires however, stability is observed to deteriorate as the response rate moves away from its optimum value.

FCAW normally operates with a steady current and a self adjusting arc over a depth range of 0...1100m using the short circuit transfer mode [28]. Preferred polarity may change from electrode positive at low pressures to electrode negative at high pressures (greater than about 7bar) depending on the wire and flux composition.

The GMAW process operates in both pulsed (constant current pulsed DC output characteristics between 0 and 100m and variable - self adjusting - pulsed DC characteristics at depths below about 150m) or steady current. The preferred polarity is electrode positive at low pressures and electrode negative with the self adjusting arc.

A recent study on the metallurgical and mechanical properties of hyperbaric GMA welds [29] has shown that the combination of a solid wire and pure argon as shielding gas produced defect free multipass welds with satisfactory arc stability. Although in this study process behaviour was not systematically investigated it was observed that process stability could be considerably improved by the addition of substantial amounts of CO_2 or O_2 to the shielding gas. However, such additions would certainly lead to unacceptable mechanical properties. Nevertheless, the process has proved to be viable for depths up to 1100m [29].

A preliminary evaluation has been carried out of welding parameters as well as shielding gas composition and their effect on the metal transfer, when duplex stainless steels are GMA welded under hyperbaric conditions using the short circuit metal transfer mode [30]. In particular, the effects of the current rise rate and current fall rate were investigated. It has been observed that the current rise rates varied between approximately 20A/ms to 40A/ms and did not produce any systematic effect on the metal transfer behaviour. Moreover, the obtained results did not show any dependence on the working pressure studied. In the case of the current fall rate however, increasing current fall rates resulted in an increase of the percentage of disturbed drop transfers. Figures 6 indicates that the faster current fall rates (and therefore higher percentages of disturbed metal transfers) were mostly associated with higher ambient pressures. Nevertheless, the results presented in this study [30] indicate that for a given welding condition, the appropriate selection of current rise and fall rates can minimise the effect of instabilities caused by high ambient pressure. The presence of active gases in the shielding did not significantly affect the metal transfer behaviour.

Offshore FCA welds carried out in the mid-seventies were made with surfaced based power sources and long welding cables. In this case open circuit voltages are of the order 60 to 85 volts. An arc voltage signal, measured at the welding torch, may be fed back to the power source in order to compensate for voltage-drops in the power cables. More recently manual pipeline welding procedures have been qualified using the FCAW process ate 360m and 450m [31]. In practice the mode of operation is exclusively the short circuit transfer.

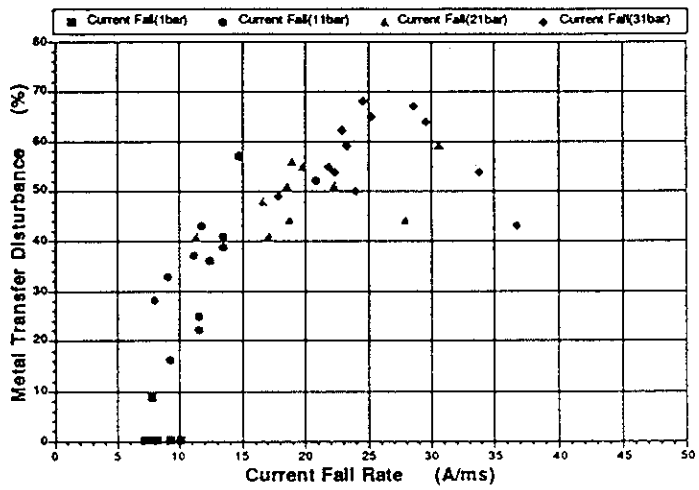


Figure 6 - Effect of the current fall rate on the percentage of metal transfer disturbances. Shielding gas: 50% He + 50% Ar.

Plasma Arc Welding (PAW)

The constricted Gas Tungsten Arc (Plasma) welding process has received little attention compared with the more widely studied free burning GTA arc. The added complexity of the process has contributed significantly to the delay in acceptance by the welding industry as a whole.

At the present time an offshore application of the plasma process has yet to be reported in the literature. However, there are a number of features which make such an application attractive. These include a high degree of positional stability and a reduced susceptibility to magnetic disturbances.

A number of authors have reported that the constricted arc operating as a 'soft' plasma (ie. with low arc forces and minimal weld pool disturbance) appears to be more stable at elevated pressures [14,19,32]. Measured in terms of lateral deviation of the anode root, at 500m the GTA arc exhibits variations of the order

50% or more of the weld bead width (depending on the design of the power pack used) compared with less than 10% for the constricted arc, the latter therefore produces a narrow weld with increased penetration. Improved stability may be attributed to the forced gas flow which replaces the natural entrainment of the free burning arc and reduces the influence of buoyancy forces in the hot gas layer surrounding the arc core.

Electrical operation is similar to that of the free burning GTAW arc. However, the constricted arc gives rise to increased energy losses and therefore higher arc voltages. Voltage is typically 2 to 20V greater than for a similar GTA arc depending on the gas flow rate and degree of constriction [27]. Transient voltage phenomena are similar to those observed during GTAW arc operation and are thought to originate primarily from turbulence in the arc column.

Arc ignition at elevated pressures may be achieved by contact between the recessed electrode and the constricting orifice. The pilot arc may be powered from a separate source or (more conveniently) from the main arc power source by incorporating a ballast resistor between the orifice and the workpiece. Ignition currents of the order of 10A are typical and the power source must provide a sufficiently stable output to sustain an arc of 1 to 2mm in length (dependent on torch geometry).

The use of the plasma process for manual welding cannot be considered in practice. High arc voltages and electromagnetic radiation levels at elevated pressures make the process better suited for automated and semi-automated applications. Constricted arc operation can offer significant advantages in terms of process stability at greater depths and together with the GMAW/FCAW is capable of consistent performance at depths below 500m.

Power sources with high operating voltages (>70V, preferably 100 - 120V) and stable current outputs at low demands are required. Typical mean current levels are of the order 60 to 100A. Current pulsing may offer advantages in terms control of the weld pool size although peak pulse amplitude is unlikely to exceed 200A due to the danger of constriction nozzle wall ablation. Pulse frequencies and duty cycles should be similar to those used in hyperbaric GTA operations.

MECHANIZED UNDERWATER WELDING

General Aspects

Since the mid-80's the offshore industry has been experiencing a substantial increase in the use of mechanised systems in underwater welding operations. The main reasons for that are:

(a) 180msw is considered to be the limit of normal diving in the Norwegian Sector of the North Sea. Extremely cost penalising regulations apply at greater depths and act as incentives for reducing the time spent by divers working at such depths [1];

(b) the consequences of environmental (pressure, humidity, breathing gas, etc.) and working conditions (restricted room, poor joint access) to the divers' physiology and psychological state;

(c) there is a shortage of experienced and medically apt welders for diving at depths greater than 180msw [1];

(d) the costs of qualifying both manual procedures and welders during onshore qualification trials in simulated depths exceeding 180msw are extremely high [1];

(e) due to the effects of pressure on the welding process, the welding arc requires particular handling techniques which make the welding operation tiring and time consuming. As a result of that, with increasing water depth, the efficiency and reliability of manual welding tends to decrease;

(e) the use of mechanized systems results in improved weld quality (more uniform welds and less risk of defects requiring repair), better assurance of weld quality in arduous offshore conditions and improved operational control and monitoring.

The widespread use of mechanized systems particularly in the North Sea has substantially increased their reputation in the industry which was initially reluctant on their efficiency and reliability. Nowadays, after more than one decade in operation worldwide, orbital welding systems are capable of producing welded joints in approximately half of the time as previously achieved with welder-divers. Figure 7 shows the time required by a modern orbital system to complete a underwater welding operation as a function of the pipeline diameter. The commercially available systems will be described later on in this section.

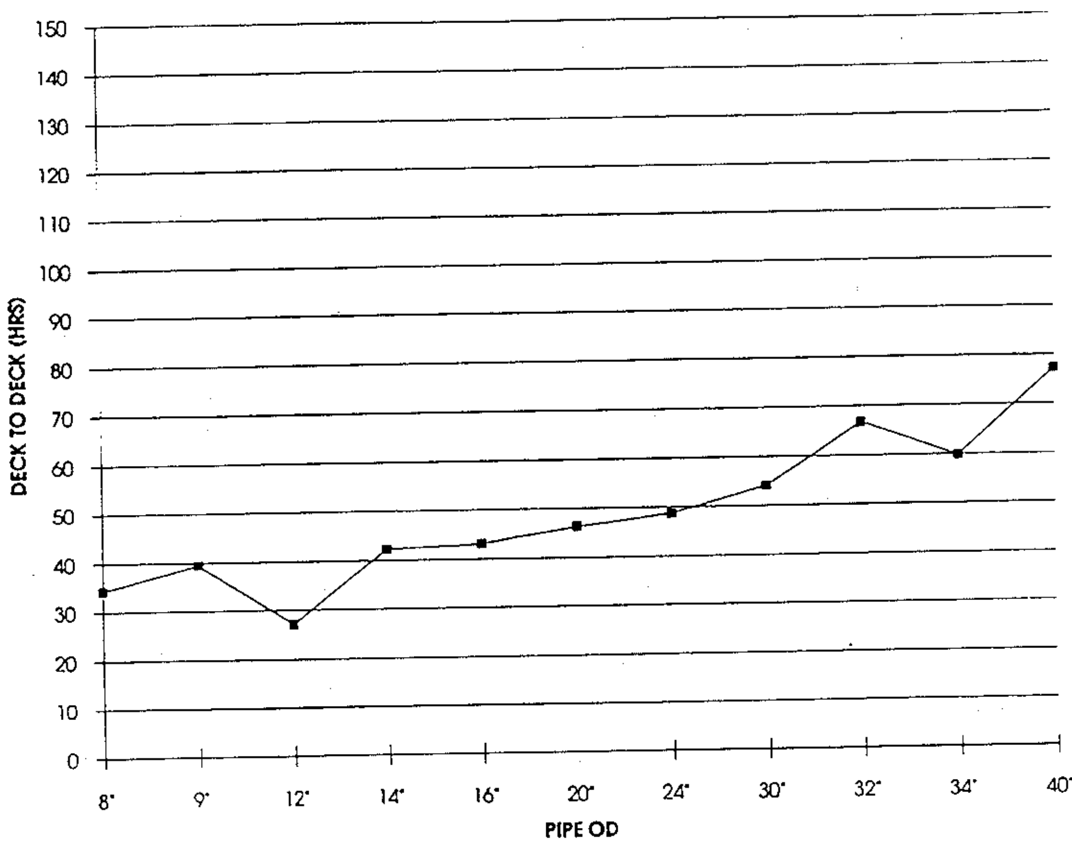


Figure 7 - Average deck-to-deck time for an underwater repair as a function of the pipeline diameter (in inches) using the THOR system [33].

Essential Elements of a Pipeline Repair Procedure

The performance of a pipeline repair underwater could be in practical terms, divided in two main stages: a preliminary one in which the basic preparatory operations (i.e.: location of the pipe, damage assessment, dredging, etc.) are carried out and an executive stage in which the repair operation and related activities take place [4]. Figure 8 shows a schematic view of typical operational stages, working phases and their respective activities. All the activities part of the preparatory stage can be performed using diverless systems [34]. For instance, damage localization is almost always carried out using pigs (tethered or tetherless) purpose equipped with geometric gauging tools, camera systems, magnetic flux leakage equipment, ultrasonic sensors (for wall thickness measurement crack detection), etc. Once the damage has been localized it is normally demarcated with passive and active markers ranging from reflectors to transponders. At this stage, a range of informations on the overall conditions at the damaged region are obtained (i.e.: if the pipe is buried or not, general bottom conditions - flat or sloping -, soil conditions, presence of obstructions - particularly sacrificial anodes -, bottom current, etc.) [35].

Pipe localization is normally carried out using either magnetic field detectors mounted on a ROV or by sonar systems usually assembled on a towed fish. Both methods are applicable to deep waters and extensively applied offshore. The remaining tasks up to habitat installation are nowadays diverless operations anyway. The literature reports, for example, the development of a range of work modules which when installed on a especially developed ROV can perform all necessary preparatory tasks in a remotely controlled mode [36]. These activities involve: dredging, pipe cutting and concrete removal (using a series of abrasive jetting and milling tools), pipe end cleaning and sealing (plug insertion) as well as the installation of beacons and guidelines.

To complete the above mentioned tasks the pipeline must be lifted from the sea floor to provide a rough alignment of the pipes and/or clearance to position the habitat with the alignment frames.

Before the actual welding operation can take place a series of crucial tasks regarding pipe preparation have to be carried out. These activities concern the removal of pipe ovality, fine alignment of the pipes, pipe cutting and machining as well as spool piece installation, alignment and support. The mechanized (diver assisted) pipeline repair (orbital welding) systems currently used offshore are able to perform most of these activities in a remotely controlled mode [37]. Most of these systems are provided with a split ring cage equipped with independently controlled hydraulic rams, each fitted with a sensor providing a position feedback signal. The "re-rounding" operation is then software controlled. The joint preparation is conventionally carried out using lathes or milling modules mounted on the rotating face plate of the pipe clamp [36].

The accurate alignment of bevelled pipe ends (spool pieces are presently generally no longer required) is performed by alignment frames.

The welding operation itself involves two additional related activities: pre-heating (and interpass temperature control) and demagnetising of the joint. The pre-heat treatment is carried out using either induction or resistance heating, temperature being controlled by thermocouples welded to the spool piece. To reduce arc blow caused by remnant magnetism hall effect probes are installed on the weld head to provide readings of magnetism in the groove. These values are then used to calculate the current supplied to demagnetizing coils set at each side of the weld [1].

Once the butt welds have been completed and tested the habitat is retrieved and the lifting frames are recovered.

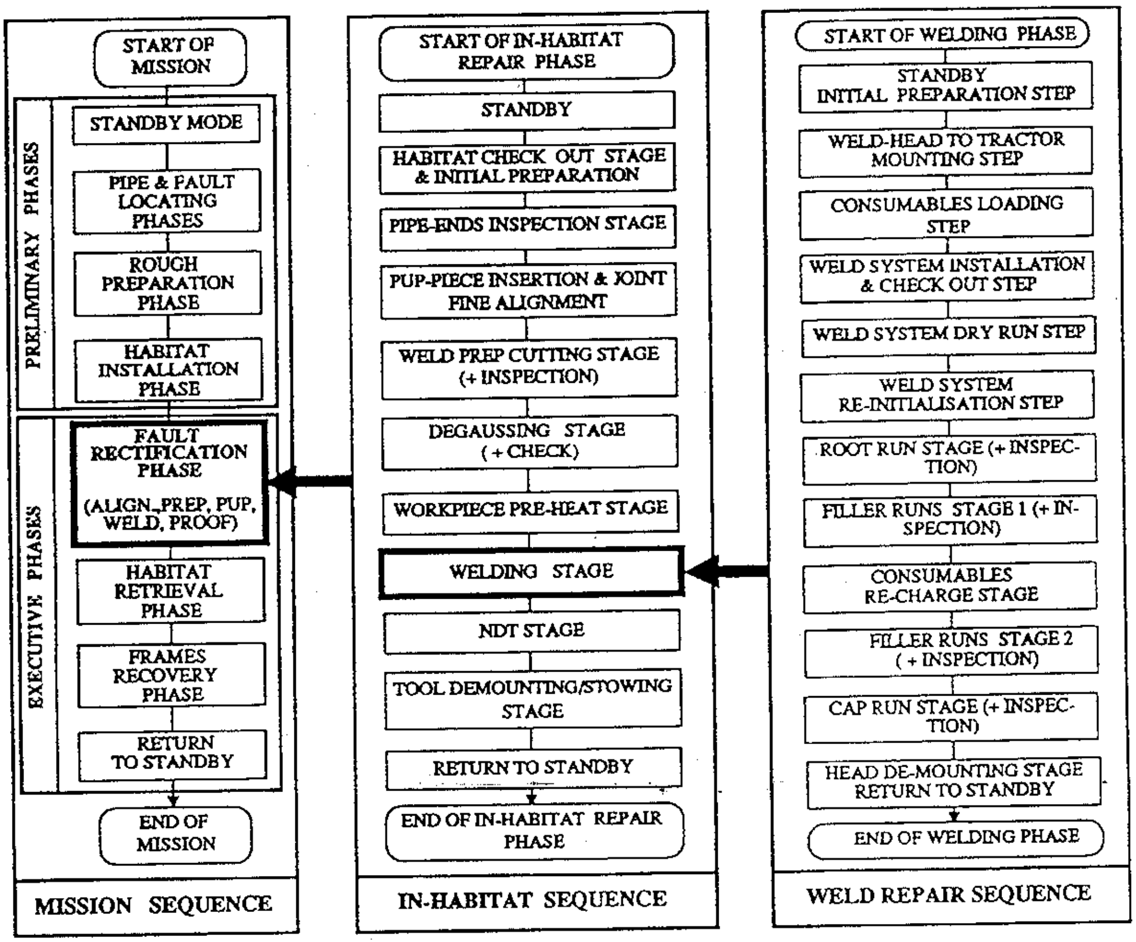


Figure 8 - Underwater welding repair procedure. Example of a repair carried out using the PRS system [4].

Orbital Welding Systems for Underwater Repair and Construction

Presently, as mentioned before, there four mechanized systems (orbital welding systems) commercially available [2-5]. These are: the OTTO Sytem (developed and operated SubSea Offshore Ltd., the THOR System (developed and operated by Stolt Comex Seaways A/S, the PRS Sytem (developed by Norsk Hydro and Statoil) and the GKSS Modular Orbital Welding System (developed by the GKSS Forschungszentrum Geesthacht GmbH and operated by MOSS Orbital Systems). These system are described in detail in this section.

The OTTO System [3,38-40]

At the heart of the system are the welding head and fixed track (Fig. 9). These are common to onshore and offshore equipment. The welding head follows the fixed track, in either sense of rotation about the pipe, while the torch is mounted on an oscillator arm. The oscillator, which also carries the cold wire feed units, permits a weaving technique to be used while welding. There is space between the fixed track and the weld preparation for pre-heat mats. The organization of the offshore system is shown in Fig. 10.

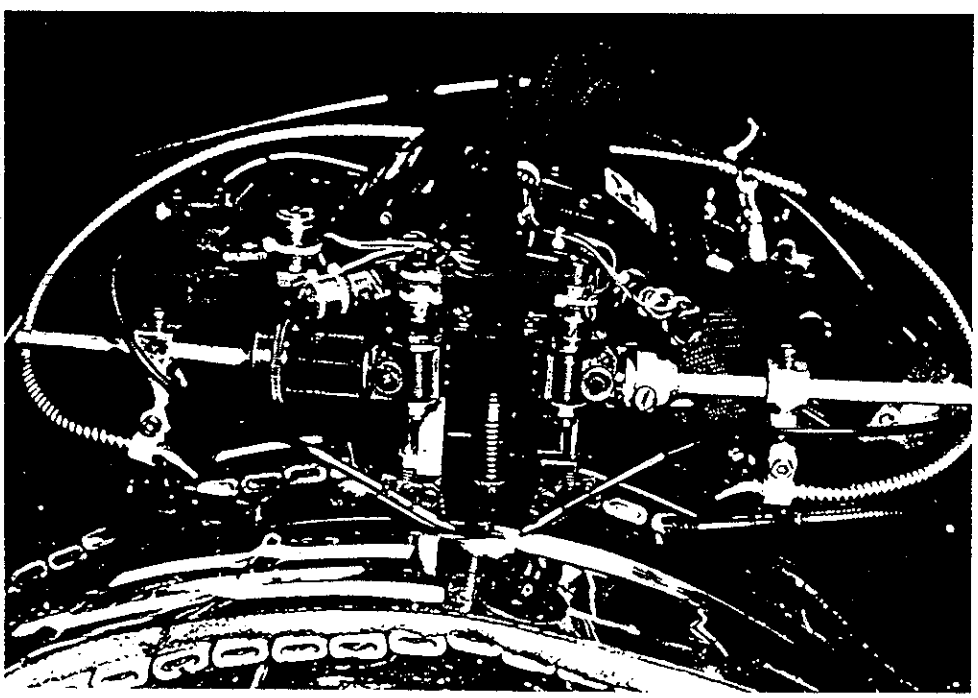


Figure 9 - The welding head of the OTTO system.

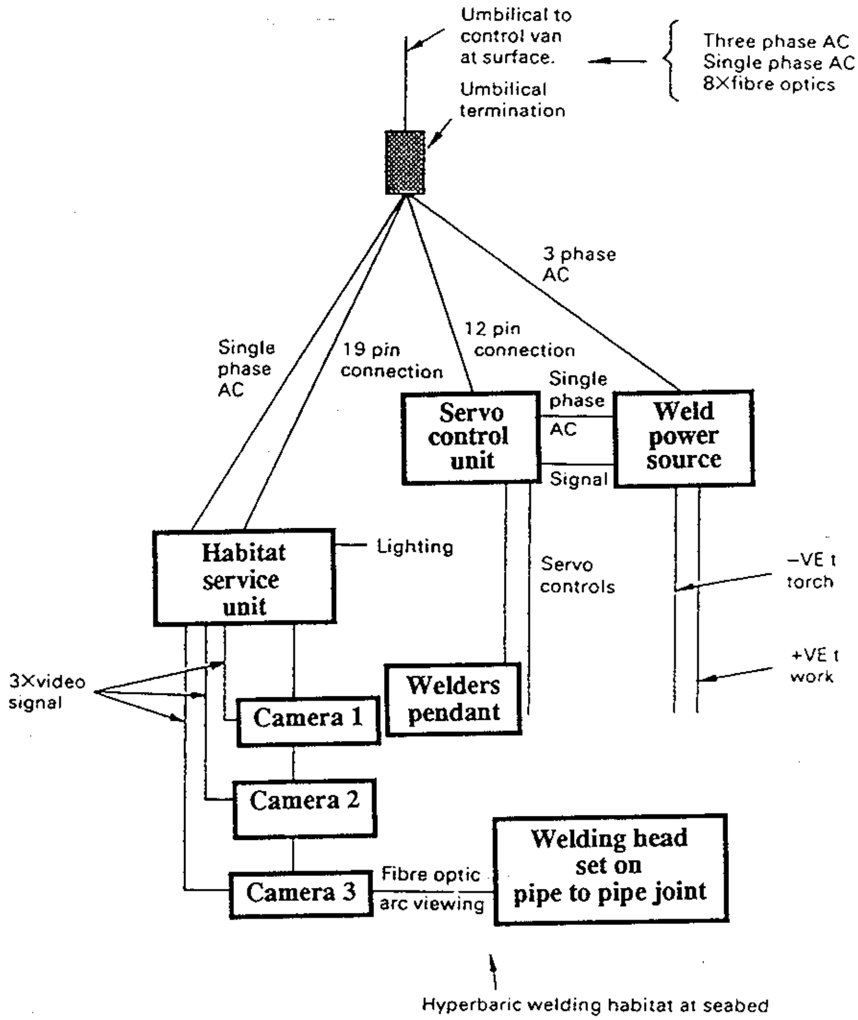


Figure 10 - OTTO, the offshore system.

Settings on the servo control unit (SCU) are made from a control panel. The SCU then controls the various mechanisms on the welding head and also controls the weld power source (WPS). Arc initiation is an example of this control.

During the initiation sequence, the tungsten electrode touches the weld preparation but it is not at this time 'live' electrically. Retraction of the electrode then begins and after 50msec power is supplied to the electrode and the welding arc initiates.

The arc current builds up to its set value after a fixed period of time (up-slope). The oscillation parameters are: amplitude of oscillation, in-dwell and out-dwell.

The arc voltage, arc current and wire feed are all pulsed. However, conventional pulse frequency need not be applied in that pulsing can be controlled by weld position while weaving. The primary function then holds for the dwell time (in or out) at the edge of the weld preparation, and the background function holds for the excursion across the weld preparation.

The cameras in the pressure vessel, which are operated in one atmosphere housings, are powered by the habitat service unit (HSU). Cameras 1 and 2 provide views of the welding set up, while camera 3 is part of an arc viewing system (Fig.9). Arc viewing is accomplished with coherent fibre optics such that the picture on the monitor in the control van is split in half. The two halves of the picture show the front and the rear of the weld pool.

A 500m umbilical connects the control van to the welding equipment on the sea bed. The umbilical contains the necessary electrical cables for electrical power but also contains fibre optics. The fibre optics are used for data transmission telemetry.

There are two computers in the SCU and two computers in the control van. This means that welding parameters can be entered in the control van (keyboard used, or a diskette) and the computer can operate the system for welding.

A diver is still required; the jobs he has to do include preparing the joint to be welded, fitting a Dearman clamp (modified for OTTO) to the pipe, fitting the welding head and fixed track to the pipe, changing tungsten electrodes, and interrun cleaning. However, the actual welding can be carried out by the OTTO system and the skill requirement at depth has thus been reduced.

The final underwater acceptance trials for the OTTO System were concluded in the summer of 1984. Since then the system has performed over 30 underwater welding operations (see Table 1).

Date	Company/Location	Description	Depth
6/84	Shell/Peterhead	OTTO Harbour trials 20"OD x 3/4"WT API5L Grade X60	55'
2/85	Statoil/Bergen	Weld Procedure Qualification 28"OD x 7/8"WT API5L Grade X65	160 m
2/85	Statoil/Bergen	Weld Procedure Qualification 28"OD x 7/8"WT API5L Grade X65	300 m
3/85	Statoil/Bergen	Weld Procedure Qualification 28"OD x 7/8"WT API5L Grade X65	400 m
5/85	Statoil/Byfjorden	Deep water trials offshore 28"OD x 7/8"WT API5L Grade X65	160 m
3/86	Tokyo Gas Company	Weld procedure trials 24"OD x 3/4"WT API5L Grade X65	30 m
5/86	Chevron/McDermott	Weld Procedure Qualifications 24"OD x 3/4"WT API5L Grade X60 sour service	610'
5/86	Chevron/McDermott	Weld Procedure Qualifications 16"OD x 1/2"WT API5L Grade X60 sour service	610'
5/86	Chevron/McDermott	Weld Procedure Qualifications 16"OD x 1/2"WT API5L Grade X60 sour service	440'
5/86	Chevron/McDermott	Weld Procedure Qualifications 10"OD x 3/8"WT API5L Grade X60 sour service	440'
9/86	Chevron/McDermott	Pipeline Tie-in at Hermosa 20"OD x 3/4"WT API5L Grade X60 sour service	610'
10/86	Chevron/McDermott	Pipeline Tie-in at Hermosa 24"OD x 3/4"WT API5L Grade X60 sour service	610'
10/86	Chevron/McDermott	Pipeline Tie-in at Hermosa 16"OD x 1/2"WT API5L Grade X60 sour service	610'

Table 1 - The track record of the OTTO system.

Date	Company/Location	Description	Depth
11/86	Chevron/McDermott	Pipeline Tie-in at Hidalgo 16"OD x 1/2"WT API5L Grade X60 sour service	440'
11/86	Chevron/McDermott 440'	Pipeline Tie-in at Hidalgo 10"OD x 3/8"WT API5L Grade X60 sour service	
2/87	Tokyo Gas Company	Weld Procedure Qualification 24"OD x 3/4"WT API5L Grade X65	30 m
2/87	Statoil/Tomm	Weld procedure trials 9"OD x 5/8"WT Duplex Stainless Steel Din No. 1.4462	0 m
7/87	Statoil/Gullfaks B	Weld Procedure Qualification 36"OD x 20.6mmWT API5L Grade X60 sour service	475 m
9/87	Statoil/Gullfaks B	Pipeline Tie-in at SPM 2 from 36"OD x 20.6mmWT API5L Grade X60 sour service	470'
9/87	Statoil/Gullfaks B	Pipeline Tie-in at SPM 2 from 36"OD x 20.6mmWT API5L Grade X60 sour service	470'
2/88	Statoil/Tomm	Weld Procedure Qualification 9"OD x 5/8"WT Duplex Stainless Steel Din No. 1.4462	75 m
7/89	Norsk Hydro / McDermott	Weld Procedure Qualification 20"OD x 7/8"WT API5L Grade X60	110 m
9/89	Norsk Hydro / McDermott	Pipeline Tie-in of Troll Oseberg Gas Injection 8TOGI) pipeline at Oseburg 2 platform. 20"OD x 7/8"WT API5L Grade X60	110 m
10/90	BP PSP	WPQ 36"OD x 20.6mmWT API5L Grade X60 - EPRS Package	137 m

Table 1 - The track record of the OTTO system (cont.).

Date	Company/Location	Description	Depth
3/91	Shell Expro (UK)	WPQ 24"OD x 15mmWT API5L Grade X60 Brentfield/Weld EPRS Package	141 m
9/91	Heeremac/Stos NZ	WPQ 20.7mm OD x 31.4mm WT API5L Grade X60 28.4mm WT 316L - 3mm WT internal cladding in the 5G position	110 m
10/91	Heeremac/Stos NZ	WPQ 20.7mm OD x 31.4mm WT API5L Grade X60 28.4mm WT 316L - 3mm WT internal cladding in the 5G position	110 m
3/92	Heeremac/Stos NZ	Pipe Tie-in of Maul A Platform 20.7" OD x 31.4mm WT API5L Grade X60 28.4mm WT 316L - 3mm WT Internal Cladding in the 5G position	110 m
6/92	Heeremac/Stos NZ	Pipe Tie-in of Maul A Platform 20.7" OD x 31.4mm WT API5L Grade X60 28.4mm WT 316L - 3mm WT Internal Cladding in the 5G position	110 m
1/93	BP URPP	Standby weld procedure for Unity Riser Platform Project WPQ 36" OD x 28.4mm WT API5L Grade X65 in the 5G position	120 m

Table 1 - The track record of the OTTO system (cont.).

The THOR-1 System [1,2,33,36,41,42]

THOR-1 consists of three main components as shown in Fig. 11.

Track and GTAW Welding Head

After evaluation of existing orbital welding systems it was found necessary to design and build new equipment more suited to arduous offshore conditions. A rapid fit track was developed which required no adjustment for pipe ovality, and a modular welding head with an open design was selected to permit rapid servicing and future integration of different orbital tools or alternative welding processes, e.g. hot wire GTAW, plasma or GMAW. The head consists of a motorised central carriage which carries modular components such as the GTAW torch, weaving heads, wire guide assemblies and two video cameras. Non-motorised carriages can be attached on one or both sides of this central unit to carry wire feed equipment and spools, making it possible to weld in both directions.

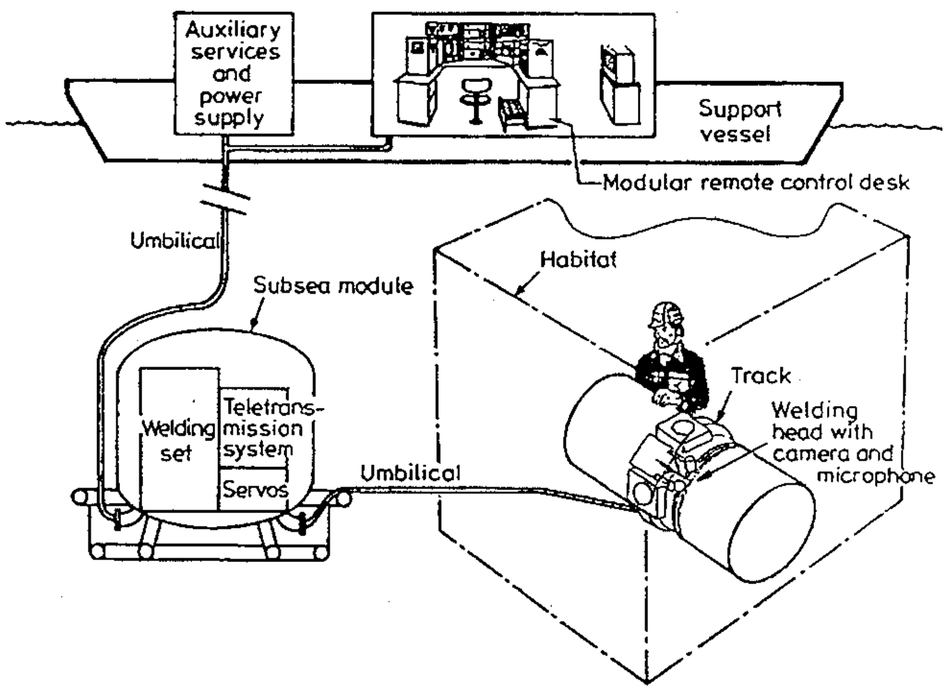


Figure 11 - The layout of the THOR 1 system.

Underwater Module

As the THOR-1 system is intended for use down to 500m, equipment such as the welding set, welding head servos and transmission terminals are located adjacent to the welding habitat on the seabed in an underwater module. A main umbilical from the surface supplies essential services for this unit and a short subsea umbilical is installed between the habitat and the subsea module (Fig. 12).

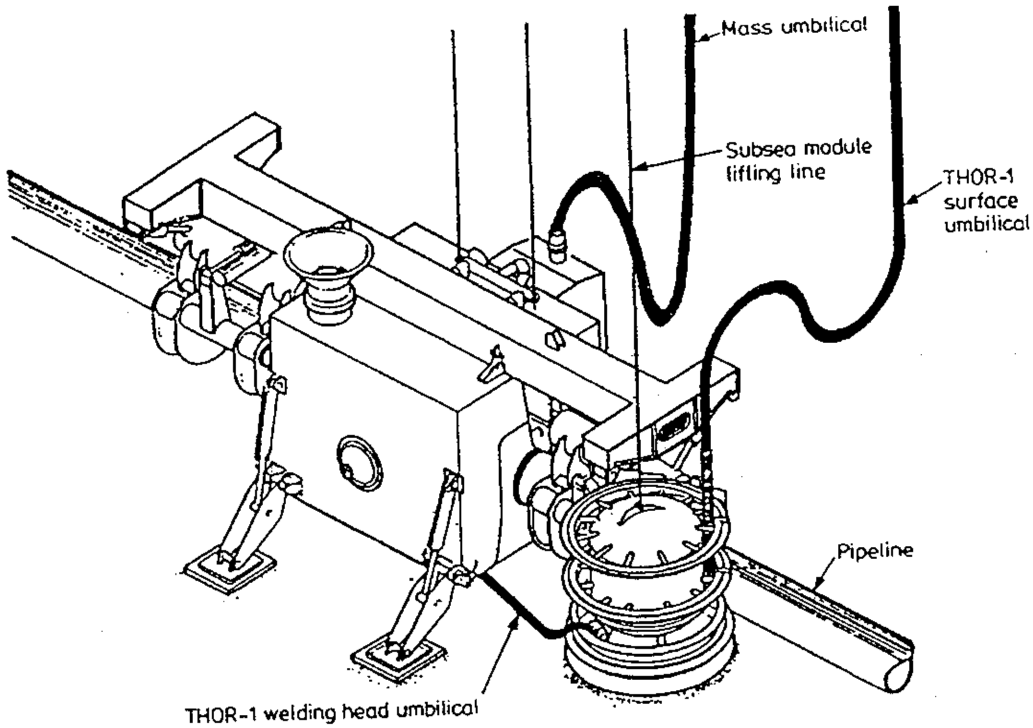


Figure 12 - Subsea module and habitat in working position.

Surface Control Module

Welding is supervised and controlled from the modular remote control desk (MRCD) which is housed in a portable container on the deck of the diving support vessel. This and all other components of THOR-1 have been designed to be independent of the diving support vessel and the type of welding habitat.

Weld Control System

The welding control system for THOR-1 is based on two microprocessors, one installed in the remote control desk (Fig. 13) and the other in the subsea module. The first of these communicates with the surface peripherals and transmits instructions to the second microprocessor which controls the functions of the welding set and welding head directly. Welding parameters are introduced into the system either via cassette or by use of a simplified keyboard and programmes are built up in sectors. Each sector length represents an actual distance of travel of the welding head on the pipe and permits use of the optimum welding parameters for each position. The extended system memory allows programming up to 50 weld passes, each consisting of a start, stop, and up to eight intermediate sectors. The operator has a full range of remote controls at his disposal for use during setup and for making real time modifications during welding. However, the value and maximum permitted number of each incremental modification of essential variables (e.g current or travel speed) are programmed to ensure that parameters stay within the qualified ranges. The operators' workstation is completed by two hardcopy printers for listing programmes or actual welding parameters, video monitors for general surveillance (monochrome), and molten pool observation (colour), and the equipment associated with the teletransmission system and control of non-welding functions.

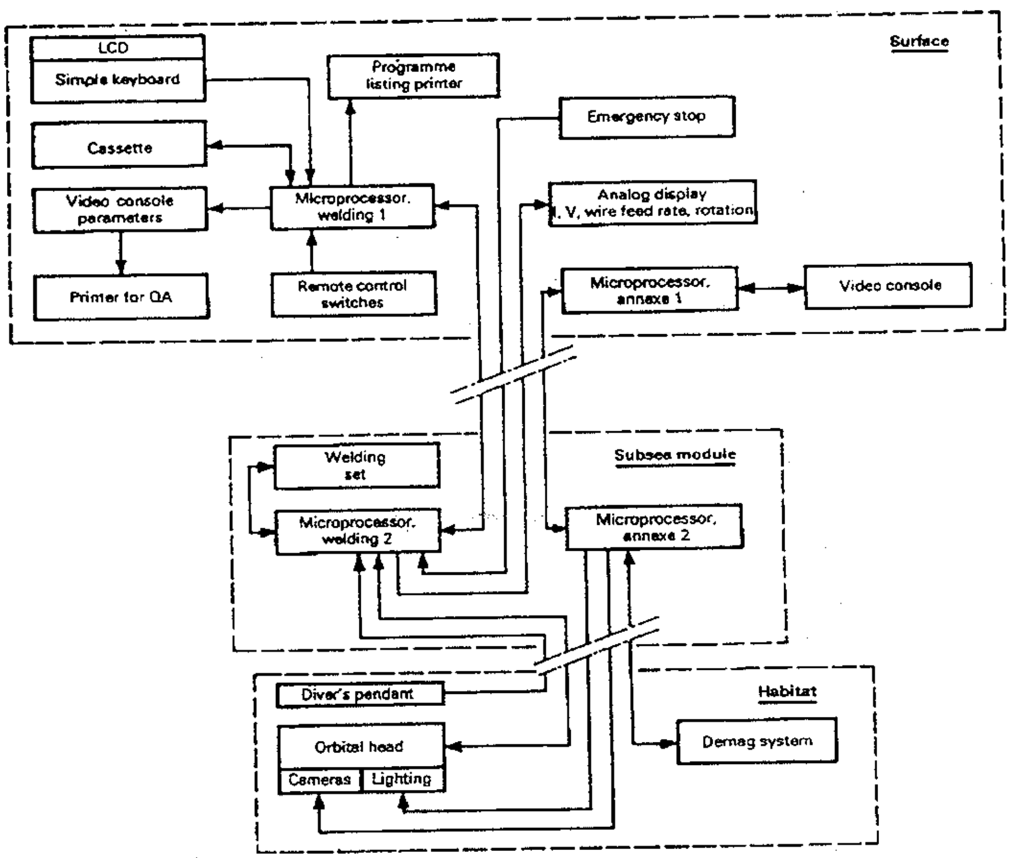


Figure 13 - THOR-1 welding control system.

Molten Pool Observation System

A vital part of THOR-1 is the molten pool observation system which uses two cameras, one giving a view ahead of the arc and the other behind. Each camera is mounted on motorised vertical and horizontal slides which are controlled from the surface so that the optimum viewing position is established for pre- and post-weld inspection as well as for the welding cycle. Colour balance, iris control and auxiliary lighting are also controlled by the surface operator.

The optical system includes a purpose built lens with up to 80mm depth of field and an optoelectronic iris. To avoid risk of interference and provide high quality images, the THOR-1 orbital head was designed so that the cameras could be housed in single units viewing the molten pool directly, eliminating need for either fibreoptic bundles or an umbilical between the chip and associated electronics.

Subsequent Developments

The experience gained during the offshore operation has been utilized in the further development of the system. An extensive data bank has now been developed which relates depth, pipe dimensions, bevel shape, root face thickness, gap and misalignment to weld parameters which will ensure a successful root pass.

Pipe preparation procedures and equipment have been developed based on a subsea lathe and a special tool box which ensure that the required "J" bevel shape and dimensions including the critical root face thickness are reproduced with the minimum of 'pipefitter intervention'.

Automatic root pass welding is also dependent on removing or nullifying the effects of remanent magnetism in the weld groove during welding. An automatic demagnetizing system has been incorporated into the THOR-1 system. Hall effect probes installed on the weld head provide readings of magnetism in the groove, and these values are used by the THOR-1 telemetry system to calculate the currents to be supplied to the two demagnetizing coils set each side of the weld. The system is now fully operational and can permit 'real time' correction of remanent magnetic fields which can vary in direction and magnitude up to 1000 gauss around the circumference of the pipe.

The THOR-1 project was started in January 1985 and progressed with design, manufacture and testing of the main components by January 1986. Following the completion phase, the equipment was installed in Comex hyperbaric test centre in Marseilles and subjected to a function test at simulated water depth of 500msw.

The experience gained with THOR-1 was further used by Stolt Comex Seaway A/S for the development of a more advanced system, THOR-2 (Fig. 14). Both systems have been used successfully since, with the achievement of an important number of tie-ins of various pipe diameters for companies like Statoil, Norsk Hydro, Amoco, Total, Elf, Phillips, etc.. Table 2 presents the track record of these systems.

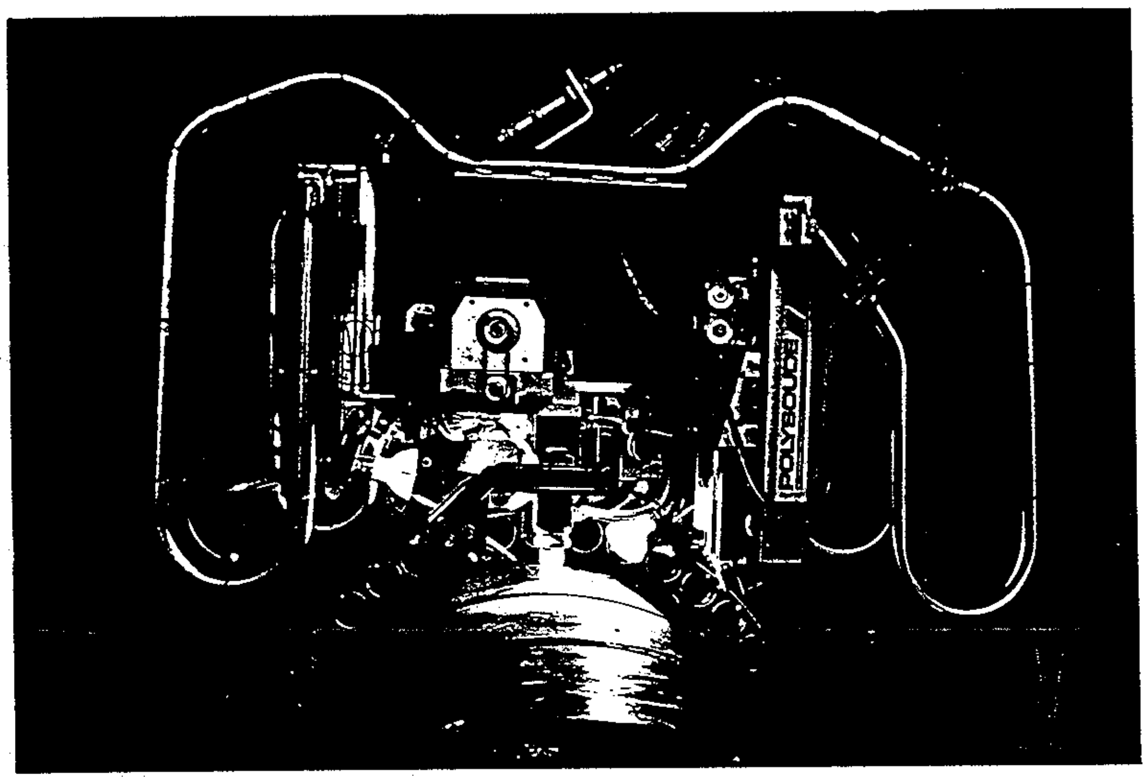


Figure 13 - The THOR-2 welding head.

Year	Country	Client	Nb of Weld	Pipe Size	Steel Type	Depth
1986	UK	Tomec Alwyn	1	24"x17.5mm	API5LX65	130msw
		TOTAL	1			
1990	UK	Tomec Alwyn	2	24"x17.5mm	API5LX65	130msw
1990	UK	Amoco Hutton	2	10"x11.1mm	API5LX60	145msw
1990	New Zealand	Shell BP Tood Oil Maui	Proc. only	20"x(19.1+3)mm	X60+316L	110msw
		TOTAL	4			
1991	Holland	Elf Nogat	1	36"x24mm	API5LX60	43msw
1991	Holland	Elf Nogat	1	36"x17.7mm	API5LX60	43msw
1991	Holland	Elf Nogat	1	24"x18mm	API5LX60	43msw
1991	Holland	Elf Nogat	1	24"x13.1mm	API5LX60	43msw
1991	Norway	Norsk Hydro Oseberg2 MTS	3	14"x23.8mm	API5LX60	110msw
1991	Norway	Norsk Hydro Oseberg2 MTS	1	14"x26.2mm	API5LX60	110msw
1991	Norway	Norsk Hydro Oseberg2 MTS	1	16"x34.9mm	API5LX60	110msw
		TOTAL	9			
1992	UK	Total Bruce	4	32"x23.8mm	API5LX60	125msw
1992	UK	Total Bruce	4	32"x19.09mm	API5LX60	125msw
1992	Holland	Elf Nogat	1	24"x18mm	API5LX60	43msw
1992	Holland	Elf Nogat	2	24"x13.1mm	API5LX60	43msw
1992	UK	Amoco Grabens	3	20"x19.7mm	API5LX60	90msw
1992	UK	Amoco Grabens	2	20"x25.4mm	API5LX60	90msw
1992	Norway	Statoil Zeepipe	1	40"x23.8mm	API5LX65	70msw
1992	Norway	Statoil Zeepipe	2	40"x30.4mm	API5LX65	80msw
1992	Norway	Statoil Zeepipe	2	40"x29.1mm	API5LX65	80msw
1992	Norway	Statoil Zeepipe	2	30"x20.6mm	API5LX65	80msw
1992	Norway	Statoil Zeepipe	2	20"x17.9mm	API5LX60	80msw
1992	Norway	Statoil Statfjord Satellite	2	9"x17.9mm	API5LX65	90msw
		TOTAL	27			
1993	Norway	Statoil Statfjord Satellite	4	20"x17.9mm	API5LX65	85msw
1993	Norway	Statoil Statfjord Satellite	2	20"x20.2mm	API5LX65	85msw
1993	Norway	Norsk Hydro Brage	2	8"x11mm	API5LX60	136msw
1993	Norway	Norsk Hydro Brage	2	12"x10.5mm	API5LX60	136msw
1993	Norway	Norsk Hydro Brage	1	8"x11mm	API5LX60	110msw
1993	Norway	Norsk Hydro Brage	1	20"x20.6mm	API5LX60	110msw
		TOTAL	12			
1994	Norway	Statoil Europipe	2	40"x29.1mm	API5LX65	36msw
1994	Norway	Statoil Europipe	1	40"x24.6mm	API5LX65	41msw
1994	Norway	Statoil Europipe	2	40"x29.1mm	API5LX65	70msw
1994	Norway	PPCoN 37/4 By Pass	2	34"x20.6&18.4mm	API5LX60	80msw
1994	UK	Total Dunbar	1	16"x17.5&22.2mm	API5LX60	110msw
		TOTAL	8			
1995	Congo	Elf N'Kossa*	1	16"x17.45mm	API5LX52	170msw
1995	Congo	Elf N'Kossa*	2	18"x17.45mm	Duplex 2205	170msw
1995	Congo	Elf N'Kossa*	2	14"x17.45mm	API5LX60	170msw
		TOTAL	5			

* to be performed

Table 2 - The track record of the THOR system.

The Pipeline Repair System (PRS) [4,37,43,44]

As major pipeline operators in the North Sea, both Norsk Hydro and Statoil saw the need of establishing a fast responding pipeline repair system (PRS) for their respective pipelines. Both companies realized that it would be cost effective to share vital/common PRS components instead of having two independent systems. As a result a joint PRS agreement was signed on October 1987.

The main PRS components are:

1. Habitat system

* Welding habitats including alignment frames (up to 42" pipeline)
* Habitat control and utility system
* Mechanized TIG welding system
* Integrated modular tool

2. Pipe preparation system

* Concrete removal machines (CRM)
* Subsea power pack (SSPP)
* H-frames

3. Split sleeve repair clamp system

* Split sleeve repair clamp installation frame
* Split sleeve repair clamps

4. Dual module hydroplugs

The mechanized welding system is described below.

Operation Philosophy

All remote-controlled operations are pre-qualified. Tolerance windows have been established based on verification of alignment and groove dimensions measurements. All manually controlled operations are done strictly to pre-qualified procedures drilled during training and qualification.

The welding operation philosophy can be summarized as follows:

• All welding is remote controlled from surface
• All parameters are pre-programmed
• Normally there are essential welding parameters during welding. If problem

arise, the welding operation is stopped and new parameters are programmed in accordance with pre-qualified procedures.

During welding the following controls are in action:

- Lateral position of torch
- Wire nozzle position lateral - vertical
- Weave width adjustment (normally programmed based on measurement)
- Start/stop of wire in emergency (re-weld afterwards)
- Repair of defects according to pre-programmed procedures

All welding is controlled by an inclinometer which allows for accurate positioning and documentation and location of defects and problem areas. Changes in welding parameters are controlled according to actual welding position .

Welding System

The orbital welding system (3 off) consists of two split rings, of which the inner ring is fixed to the pipe with adjustable feet. The outer ring which runs on the inner ring carries the orbital drive unit, welding head, inclinometer and welding wire. The orbital welding system is transported to the habitat inside the TRACO, (transport container) together with the weld heads.

Bevel Preparation is made with a hydraulically driven Roberts Brothes Machine. The machining might be done either inside the habitat, in the dry or in the water. The Roberts Brothers Machine is secured squared on the pipe with four feet. The pipe cutting tool is mounted on the toolbracket on the rotating ring of the machine. The pipe is then cut at proper location. The cutting tool is removed and the counter bore and bevel tool is mounted on the toolbracket. The counter bore is made first. The intention with the counter bore is to achieve a perfect circle inside the pipe, and a clean surface. The minimum pipe wall thickness allowable must be established prior to machining, and as little metal as possible shall be removed. Ideally the inside diameters for both pipes to be welded should be the same. The tool for the bevelling is placed on the same tool holder as the counter bore tool. The tool is mounted to give the correct angle of bevel. Having completed the machining, the bevel is checked every hours around the circumference to see if it is inside the specifications. The feet on the inner ring are pre-adjusted on the surface prior to being sent down to the habitat in the TRACO. The inner ring is mounted square on the pipe first, at a pre-established distance from the weld. The outer ring is then mounted on the inner ring. The preheat is mounted on the pipe.The drive unit for the system is mounted on its designated support, and the drive is locked to prevent unintentional rotation. The weld head is then mounted with the welding wire, and the the inclinometer. Finally the welding umbilical is installed between the POCO flange and weld head. The welding is controlled from the surface power and control cabin. When the first weld has been completed and NDT performed, the orbital system will be moved to the other pipe, weld head mounted and the second weld performed (Fig. 14).

The sub-systems can be listed as follows:

- Welding power sources
- Welding control system
- Welding observation system
- Degaussing system
- Welding heads
- Shielding gas

All basic sub-systems are used for procedure development including control systems and power sources. Figure 15 presents an schematic view of the system.

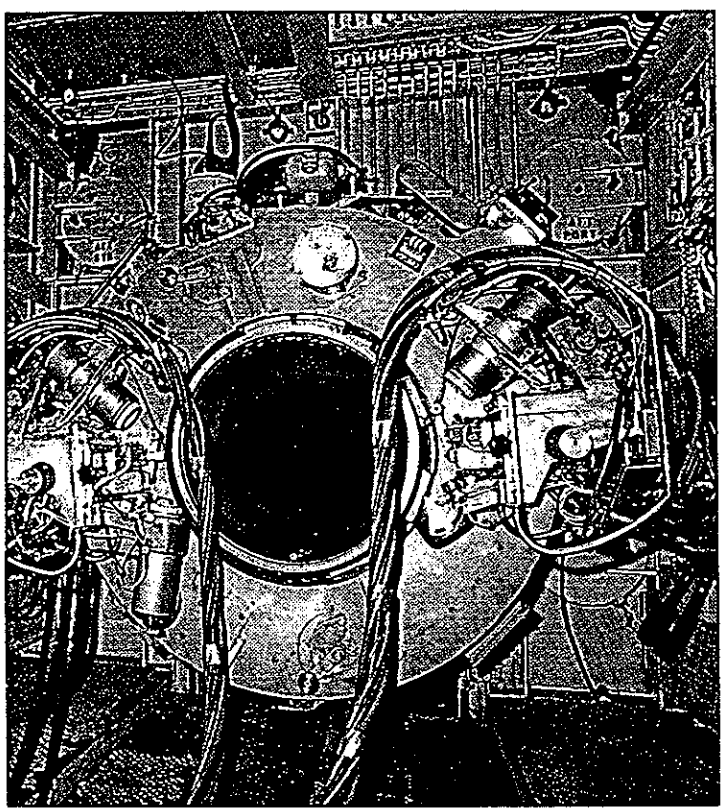


Figure 14 - The IMT - a fixture for constraining and preparing the pipe ends and for welding - installed in the habitat

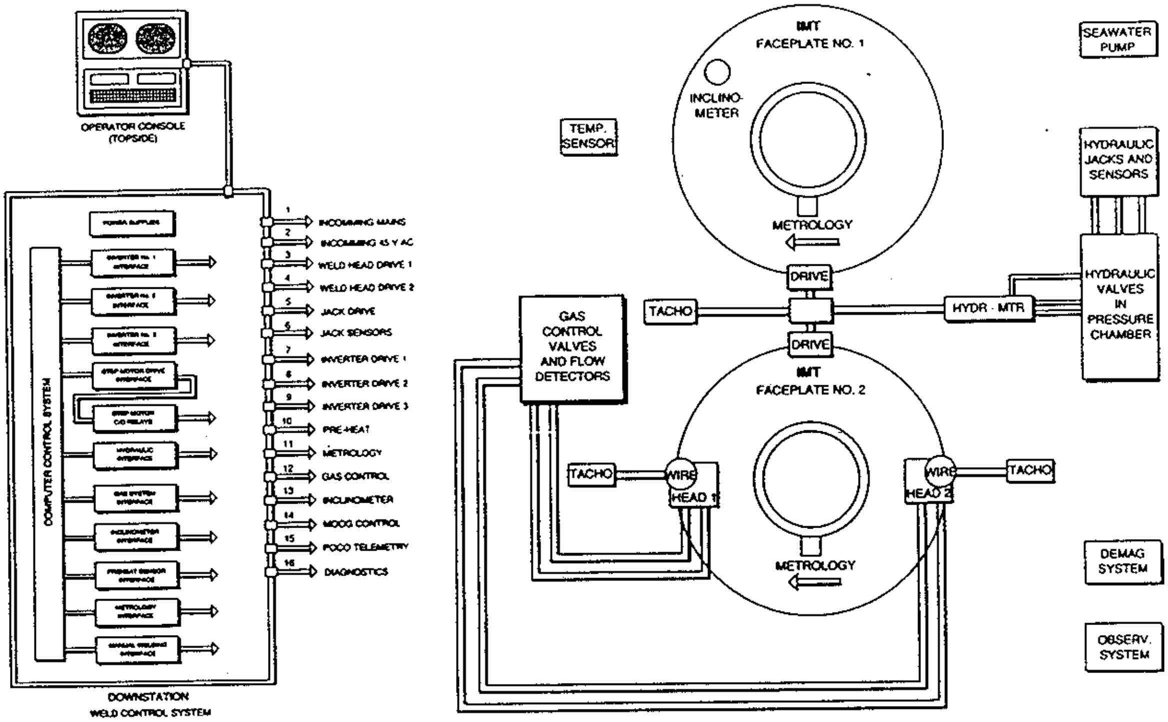


Figure 15 - A general overview of the system.

Welding Power Sources

The power sources are rated for 35kW induction heating at 300A and 65V welding. The power sources are of full bridge thyristor inverter type with 12 kHz resonance frequency. Thermal efficiency is better than 80%. Accuracy of voltage and current is better than 1% of full scale typical + 1V and + 1A. The inverters are purpose built to fit in a one-bar container of 500 mn OD and main cooling is by seawater circulation.

Welding Control System

The welding control system is an advanced menu driven system based on an IBM PC as main computer. All real time control is done by an Intel 386 processor on the seabed to minimize communication. During welding only status information and changes are shared between the processors.

The control system also contains a number of purpose built interface cards to drive motions and to run the power sources.

The following main features are controlled:

- All welding parameters and motions
- Preheat
- Round up of pipe using 8 x 25 tonne screw jacks
- Configuration of power sources (3 power sources)
- Welding pass sequencing
- Configuration of welding heads
- Calibration
- Metrology
- Configuration of shielding gas valves

Welding Observation System

The welding observation system is used by the surface operator to follow the actual welding. It is based on standard colour CCD camera with specially built lens and filtering system. All functions are controlled by a RS422 data link. All servo functions are built into the camera housing designed for 40 bar external pressure. Two cameras are used on each welding head. A specially developed polarized local filter gives possibility to dampen the light from the arc itself without darkening the surroundings. This gives a very good picture.

Degaussing System

The system is based on a standard zeromag system which is mounted into a one-bar container. Control of the system is done through the POCO transmission system (PTS system).

The degaussing system controls the magnetic field within the groove to prevent remanent and earth magnetism in the pipe material from adversely affecting the weld arc. This is done by making opposite fields using coils around the pipe. The current in the coils is controlled by a signal from a hall-probe in the groove in front of the welding torch. The hall-probe measures the magnetism and can also be used for measurements prior to welding. The operation of the degaussing system is either automatic or manually controlled.

Weld Heads

The weldheads are heavy duty driven by step-motors for accuracy and reliability. The GTAW-torch is specially designed to allow quick change of torch body including tungsten electrode and gas nozzle in one unit. This design can be developed further towards remote-controlled change of the torch unit. The weldheads carries two observation cameras front and aft of the weld (Fig. 16).

The following functions are included:

- Torch lateral and vertical movement +25mm
- Wire nozzle guide lateral and vertical movement +10mm
- Wire feed 0 - 20 m/min. 0.8 - 3.2mm wire.

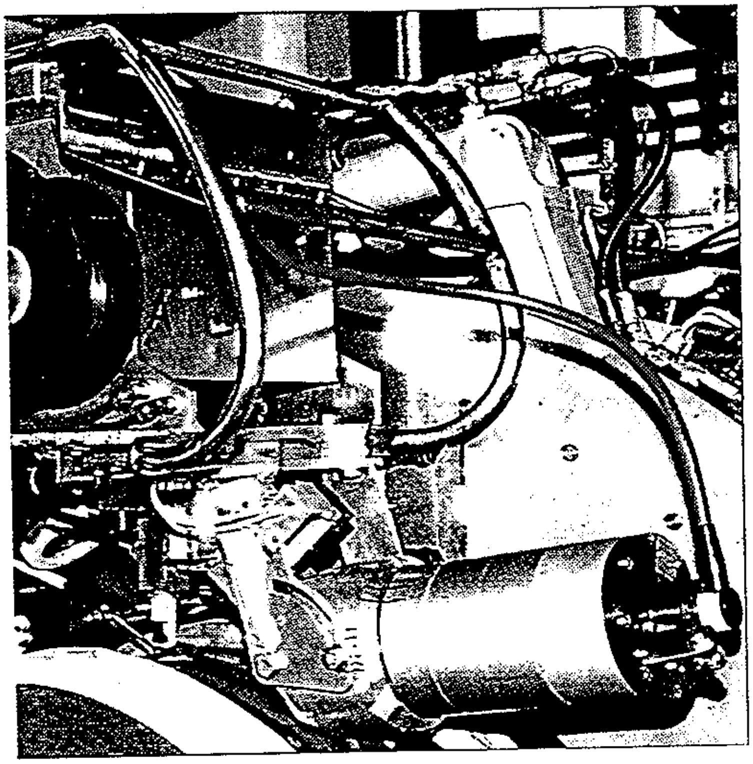


Figure 16 - Detail of the weld head.

The original motivation to develop the system was formulated in 1984-1985. The development started in 1984 and a number of areas had to be developed and prototype tested prior to implementation by the diving contractor for commercial use. The following were the main areas of development. The prototype testing was finalised by a full scale test to 360 msw at NUTEC (Bergen, Norway) of the welding system in 1986. The system carried out its first production weld in 1988 during tie-in of the 28" oil Pipeline to the Oseberg 'A' platform in the Norlh Sea. Up to 1991 the system was used for 16 production tie-in welds in three projects:

- 1988; Norsk Hydro Oseberg 'A' pipeline tie-in, 2 welds at 110msw.
- 1989; Statoil Gullfaks 'C' pipeline tie-ins, 6 welds a 220 msw.
- 1990: Norsk Hydro Oseberg 2 pipeline tie-ins, 8 welds at 110 msw.

Stolt Comex Seaway A/S has been the diving contractor and operator of the system for all three projects. Table 3 shows the operational welding time for these welds.

Subsequent Developments

In the course of 1994 a series of improvements have been introduced to the PRS system with the objective of reducing the diving related activities in welding operations. All the systems actuating outside the welding habitat are now operated from the the surface, i.e. diverless. This new configuration of the PRS is known as the "dry" PRS.

Weld Location	Pipe Diameter (OD x WT)	Operational Welding Time
Oseberg 'A' Riser	28" x 30.2 mm	23 hrs 53 mins
Oseberg 'A' Pipeline	28" x 30.2 mm	17 hrs 36 mins
Gullfaks 'C' Riser	12" x 14.3 mm	4 hrs 20 mins
Gullfaks 'C' Riser	10" x 22.2 mm	6 hrs 3 mins
Gullfaks 'C' Pipeline	10" x 18.3 mm	4 hrs 16 mins
Gullfaks 'C' Pipeline	12" x 12.7 mm	4 hrs 22 mins
Gullfaks 'C' Riser	36" x 25.4 mm	13 hrs 50 mins
Gullfaks 'C' Pipeline	36" x 25.4 mm	12 hrs 7 mins
Oseberg 'A' Riser	16" x 22.2 mm	4 hrs 45 mins
Oseberg 'A' Pipeline	16" x 18.1 mm	4 hrs 45 mins
Oseberg 'C' Oil Riser	16" x 15.9 mm	4 hrs 58 mins
Oseberg 'C' Oil Pipeline	16" x 14.3 mm	3 hrs 49 mins
Veslefrikk 'Y' Pipeline	16" x 11.1 mm	3 hrs 48 mins
Oseberg 'C' W.I. Riser	16" x 22.2 mm	4 hrs 5 mins
Oseberg 'C' W.I. Pipeline	16" x 18.1 mm	5 hrs 0 mins
Veslefrikk 'Y' Assembly	16" x 15.9 mm	4 hrs 14 mins

Table 3 - Operational welding time with the Pipeline Repair System.

The GKSS Modular Orbital Welding System (MOSS) [5,26]

Experiments have shown that commercially available 1-bar orbital systems do not meet the requirements posed by applications under hyperbaric conditions. To achieve satisfactory levels of performance and reliability expensive modifications are essential. To avoid such modifications a new fully mechanized orbital welding system was designed and constructed. The main design criteria for the MOSS were:

(a) the system should be simple and robust to meet the rough offshore conditions,

(b) the driving unit for the orbital head has to be very accurate and guarantee precise performance especially for the production of acceptable root pass welds with large root gap tolerances [45],

(c) the components of the system have to be of pressure and corrosion resistant material, to withstand the rough and corrosive hyperbaric condition in the habitat,

(d) the system must be very flexible especially considering the application of additional components (such as seam tracking systems, NDT-systems etc.)

(e) the design has to meet the requirements and comply with safety restrictions of standards and regulations for underwater work [46].

The present configuration of the MOSS system allows for welding operations only. This design philosophy is in line with the new developments in underwater technology, whereby activities such as concrete removal, pipe cutting, joint preparation and removal of pipe ovalization are performed by ROV's equipped with different working modules. Therefore, compact and easy-to-handle systems are nowadays more attractive to offshore operators than the multipurpose systems of the 80's.

Orbital Unit and Weld Head

The result of this development work is presented in Fig. 17. The orbital ring is a solid annular self centring track formed by two semi-circular sections coupled to each other through four tension levers. The orbital ring contains 4 to 6 pairs of adjustable clamps (at 90° intervals) which provide compensation for pipe OD variations of up to ± 40mm. The track is made of anodized high strength aluminium. The clamps and the tooth rack are made of corrosion resistant Chromium-Nickel steel. To cover the pipe diameter range from 300mm up to 1000mm four rings are required with the respective adjustable clamp sets (Fig. 18).

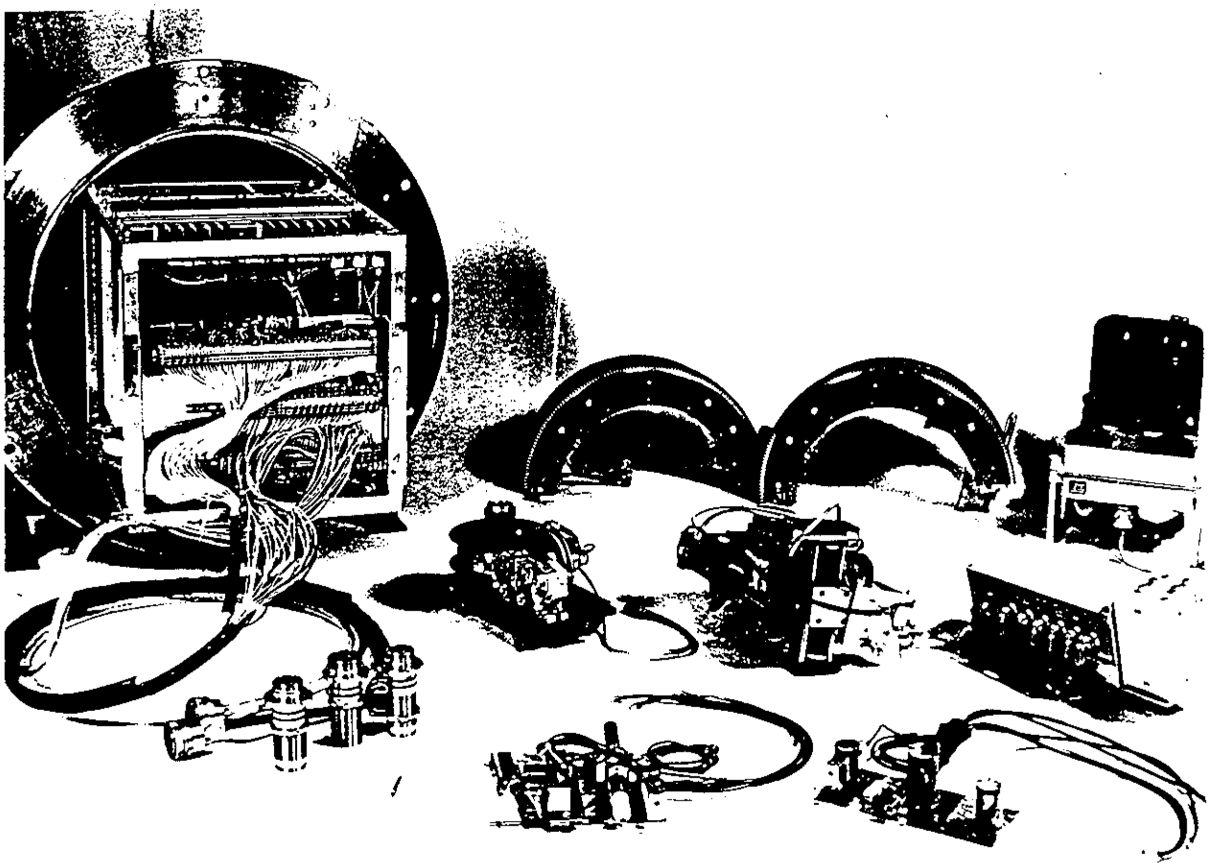


Figure 17 - The GKSS Modular Orbital Welding System.

The orbital ring also includes three independent carrier units in which various components are mounted. On the first carrier (Carrier 1) are all the supplies (energy, shielding gas and coolant), video pre-processing electronics and electrical connectors. On the second carrier are assembled the main drive, and two modules for weaving and torch height. The second carrier has also a mounting plate for the two weld head modules presently used: the GTAW (Gas Tungsten Arc Welding process) and the GMAW/FCAW (Gas Metal Arc Welding or Flux Cored Arc Welding processes). The third carrier transports the wire feed unit and the filler wire spool.

A 42V DC motor is used to drive the orbital head (and carriers) along the track ("y" axis) with programmable speeds in the range from 0 to 900mm/min (precision: < 0.1mm/min). The power from the main drive is transmitted to the track by a rack-and-pinion system which guarantees a smooth and exact progression of the weld head. A linear slide mechanism operated through a 24 V DC motor provides "x" axis torch motion (i.e.: weaving movement). The maximum weaving width is ± 50mm which can be achieved with weaving speeds of up to 1000mm/min (precision: 0.1mm/min). A second slide mechanism also operated through a 24V DC motor provides "z" axis movement (torch module height). This mechanism allows a weld head dislocation (perpendicular to the pipe surface) of 75mm. The filler wire is driven on both processes by a four wheel feed unit driven by a disc motor (rated voltage: 36V, control range: 0V to 10V, precision: 0.001V) and capable of feed rates up to 20m/min.

The two weld head modules presently used (one for each welding process) have an identical mounting plate and supply connections (i.e.: shielding gas, cooling water, wire feeder etc.). As a result of that only a few manual operations are necessary to exchange modules whenever a different welding process is required. Both weld heads are also fitted with two specially developed compact CCD cameras mounted on each side of the welding head (at the front and rear of the welding torch). The cold wire feed for the GTAW-module can be remotely adjusted in three axis by three servomotors. That enables the operator to position the filler wire exactly into the weld bead centre which is of special importance for larger root gaps. Both welding torches are water cooled and rated to 400A.

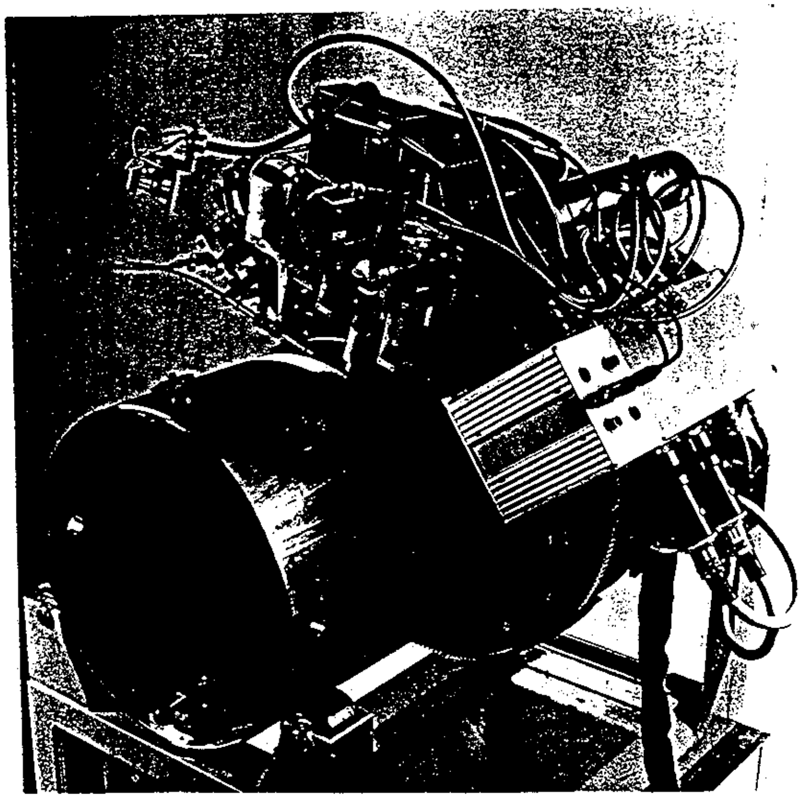


Figure 18 - The orbital ring and the weld head.

Control and Monitoring Systems

The system used to control the operation of the weld head as well as the power source is schematically presented in Figure 19. This control system could be basically divided into two sub-systems: a surface control station (SCS) and a underwater processing station (UPS).

The SCS consists of four monitors (two for arc and weld pool observation and two for habitat observation) and a central programming unit (CPU), Fig. 20. The CPU has an operational programme which provides the ability to create, modify, save, load, print, store, display and erase weld programmes. The weld programmes include the ability to change any of the primary weld and weaving parameters to different values in each of 10 different time or angle defined periods, for each pass. Furthermore, a full synchronisation between orbit and welding parameters is also possible (i.e.: specific welding parameters at groove sidewalls, etc.) . In addition to that the control software also allows the real time modification (within permissible ranges defined in a given weld procedure specification) of selected weaving and welding parameters through two joy-sticks and a "touch screen" monitor. A support programme displays and stores all relevant welding and weaving data (measuring frequency selected according to the type of variable being observed) for documentation and Quality Assurance purposes.

The UPS is basically a pressure housing, part of the underwater habitat, where the following components are installed: a Intel 80386 mother board, with a 80387 coprocessor, positioning controller and the respective motor boards (orbital drives), a multi I/O board and a serial interface. The UPS is responsible for the following tasks: control of all orbital related motors (orbital drives and cold wire positioning motors), communication between SCS and power supply controller, operation of the hand-held pendant, transfer of process data to the SCS.

Energy supply and communication (RS 485 serial interface) between SCS and UPS are carried out through an umbilical which allows data transmission up to 1000m.

The welding power source consists of an analogue transistorized power pack with an open circuit voltage of max. 80V. This unit consists of a transformer/rectifier, a bank of electrolytic capacitors, a precision linear amplifier and a transistor cascade in common collector circuit.

The power source controller supports both the GTAW and GMAW. This unit receives the "parameter sets" stored on the SCS and regulates the power output

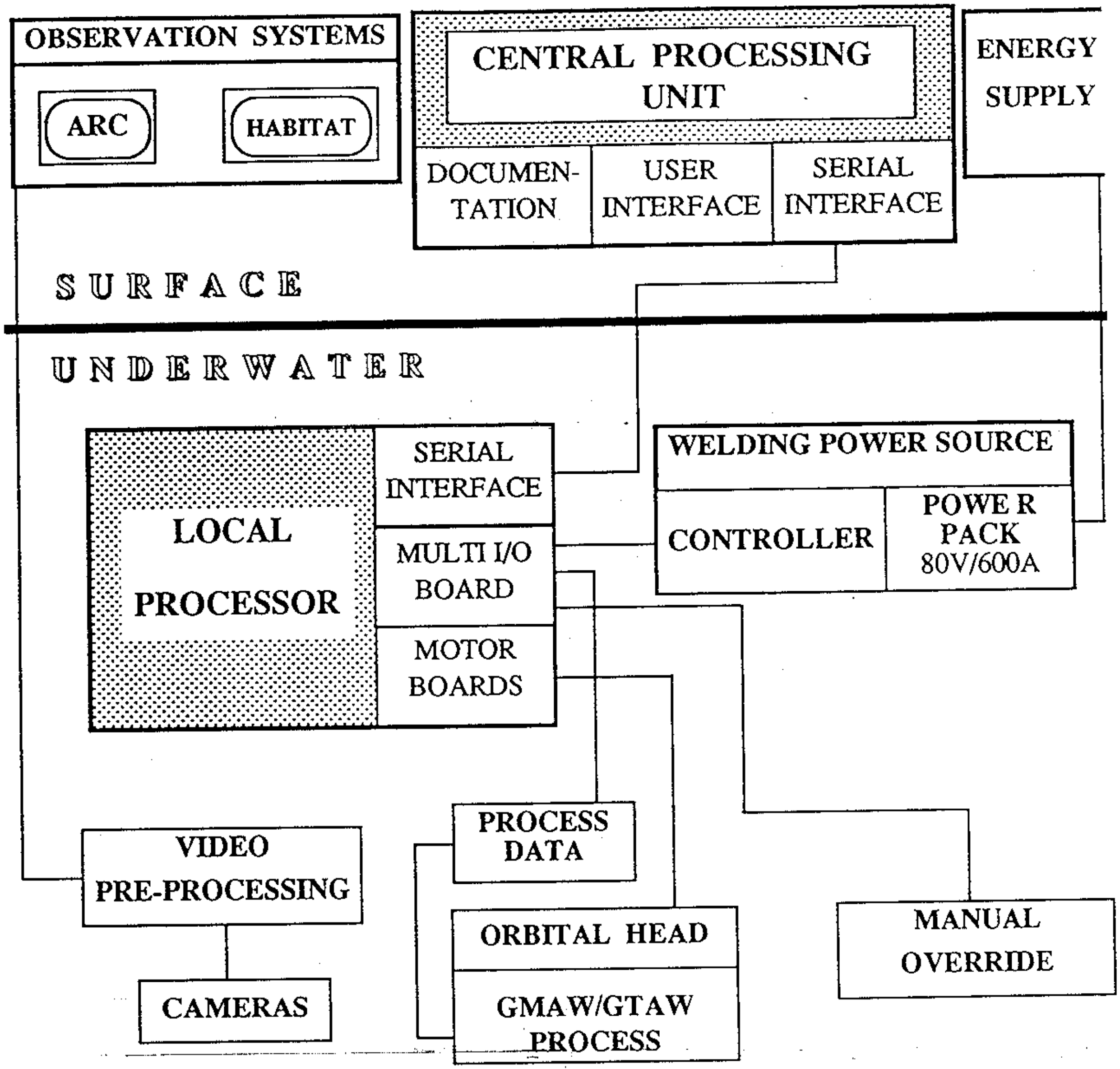


Figure 19 - Schematic description of the control structure of the Modular Orbital Welding System.

accordingly. For the GMAW process this unit is fitted with an analogue circuitry which allows the control of individual phases of the process such as current rise rates, current fall rates open arc periods, etc.

The MOSS has been successfully qualified down to 500m simulated water depth in 1992 in cooperation with PETROBRÁS S.A. . The offshore qualification of the system was also carried out in cooperation with PETROBRÁS S.A. in 1994/5 in 30msw (Fig. 21).

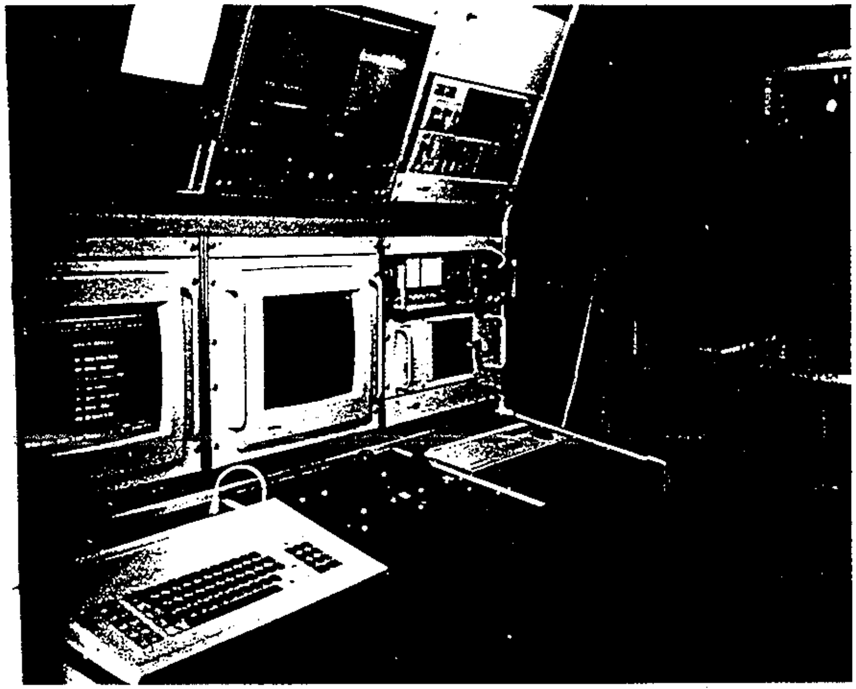


Figure 20 - The Surface Control Station.

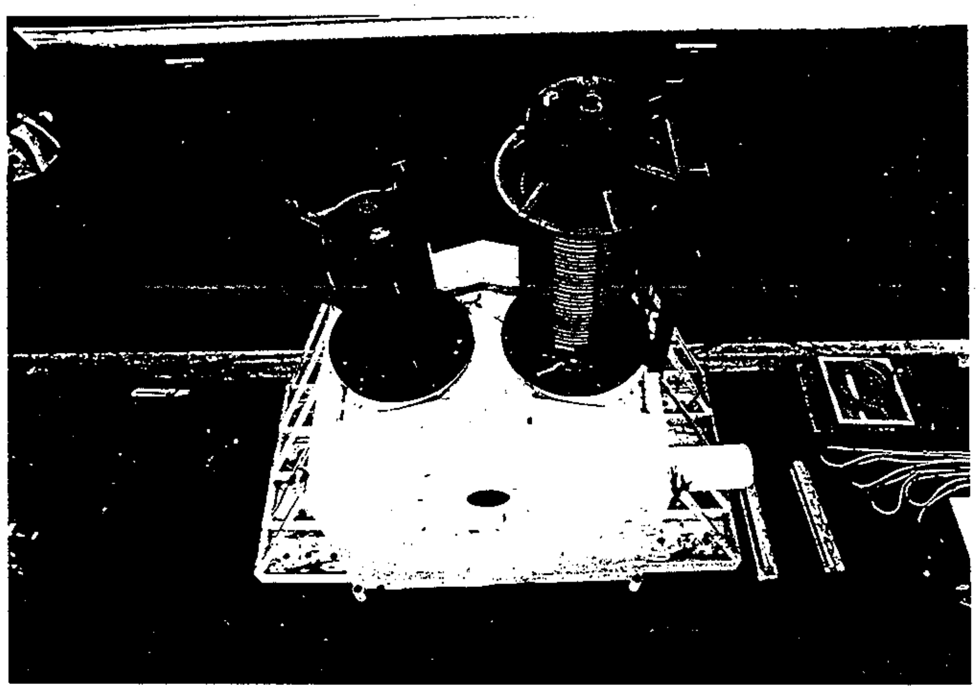


Figure 21 - The underwater processing station (yellow pressure vessel, left) and the welding power source (yellow pressure vessel, right) mounted on a mock-up habitat for the qualification tests at 30msw.

DIVERLESS SYSTEMS

Introduction

The actual depth range in which a pipeline repair work could be performed is still more or less behind the depths in which pipelines are laid.

Taking the Mediterranean Sea as an example, more than 80% of its area lies on depths exceeding 200m and more than 50% at 1000m. In addition to that an increasing number of new fields are being discovered in depths beyond 500m in the Mediterranean [47] and at the Campos Basin in offshore Brazil [48]. Operators hesitate to exploit these resources without contingency procedures for pipeline repair and maintenance since an eventual pipeline failure in deep waters could have dramatic consequences to the environment and production. Moreover, 180m appears to be the limit for offshore manned intervention, at least in the Norwegian Sector of the North Sea [1]. It seems evident that pipeline repair concepts for water depths greater than 300m - 400m must focus on robotics and remote sensing if repair intervention is going to catch up with the capabilities that already exist in the drilling, production and transportation phases of the offshore petroleum industry.

The two different diverless underwater repair methods generally considered for deep water repairs are: mechanical connectors and hyperbaric welding. Various repair systems based on mechanical connectors have been designed, such as the TITUS system [49]. Mechanical connectors are believed to offer slightly better pre-conditions for automation than hyperbaric welding and as a matter of fact, some of the available systems have already undergone offshore trials. However, they also present some disadvantages such as the requirement for accurate metrology of the contact surfaces, the probable need of dummy nodes and the lack of mechanical strength. Moreover, the efforts for pre and post repair activities offers no additional time benefit [50].

Currently, hyperbaric welding is still the best known repair method either as a manual operation (carried out by welder-divers) or as diver assisted mechanized welding. Manual pipeline welding has been successfully qualified at 450m simulated water depth in accordance to British Standard 4515 and API 1004 [1]. Mechanized orbital welding systems are presently successfully operated down to 500m depth as discussed in the previous section. The high technological level and reliability achieved in underwater welding have already encouraged the development of a system using an orbital welding set-up assisted by a manipulator which can form the basis for a future diverless repair spread [42]. However, more relevant to repair in deep waters are the satisfactory results obtained with a robotic station down to 1100 msw [51] using the GMAW process.

The growing potential of hyperbaric welding associated with the recent developments in robotics for underwater work suggested an additional alternative for a diverless repair station. This repair station, consisting basically of robots and manipulators to prepare the pipe and to weld the pipe ends, would be assisted, controlled and monitored by devices currently used in underwater work such as ROV's.

This section presents the fundamental developments in robot technology to allow for underwater operations, concepts of diverless repair stations, its main sub-systems and some aspects of the repair procedure.

<u>Robots for Underwater Work</u> [52,53]

Presently there are a series of commercially available hydraulic manipulators for underwater use operating with controllers of various degrees of precision. However, for tasks such as cutting, welding and NDE advanced handling systems are required which can be controlled and supervised from the surface and supported by sensors and off-line programming.

Development of an Underwater Robot

The strategy to develop an underwater robot was to use commercially available systems and components as far as possible and only to modify parts for the new field of application like water and pressure. Following this objective a six degrees of freedom electrically driven industrial version of the SIEMENS-MANUTEC robot type rl5 was chosen to be modified. This robot is one of the most versatile computer aided handling systems and promised to meet all the requirements for subsea application [54].

Starting from this version a pressure compensated robot had to be developed for subsea use, that means all components had to be improved to withstand the depth-corresponding pressure. At first several sub-systems had to be tested under the specified pressure up to 110bar in a suitable compensation fluid. The principle goals of testing were focused on the safe function of the mechanical, electrical and electronic robot components.

The evaluation of these tests led to necessary modifications of the robot brakes, the optical positioning sensors in each axis and some limit switches to meet the requirements of the pressurized and flooding operation. Only the electrical servo-motors have shown no influence in function under pressurized fluid. Certainly additional sealings and gaskets for the separation of the inside and ambient media had to be included in the robot construction as well as suitable underwater electrical connectors and cables. The experimental results of component tests were used to outfit one robot forearm [55-57]. This 3-axes-subsystem was operated in dry and wet environment under simulated depths in several steps down to 1100 msw [58]. After its successful testing this forearm was used to complete a 6-axes-robot based on the forearm results and further improvements. This robot was operated in an extended test program.

In a cooperation program the Institute for Production Engineering And Machine Tools (IFW) of the University of Hannover developed a new subsea control system [59]. In order to extend the operational distance between controller and handling system the control unit is divided into a desk-based and a subsea part (see Fig. 22). The design of the communication system and the submerged controller was based on the following demands:

-short signal delay for fast process and system control,
-small data rates to the desk-based control part,
-high autonomy of the underwater vehicle.

Underwater Robot: Testing and Results

The subsea robot was tested at the GKSS Simulation Plant. These tests were devised to simulate atmospheric and habitat conditions as well as shallow and deep water conditions down to 1100 msw.

The robot was connected to a simple fluid filled passive compensating system which is designed for pressure balancing including temperature effects. Parameters in the test series were:

-ambient gas (habitat) and water;
-temperatures between 4 and 30 °C;
-pressure range 1 to 110 bar;
-long time submerged operation at 110 bar;
-oscillation and break down of the electrical mains voltage;
-soft collision of the robot hand;
-still and current water up to 1.1 m/s flow velocity (see Fig. 23).

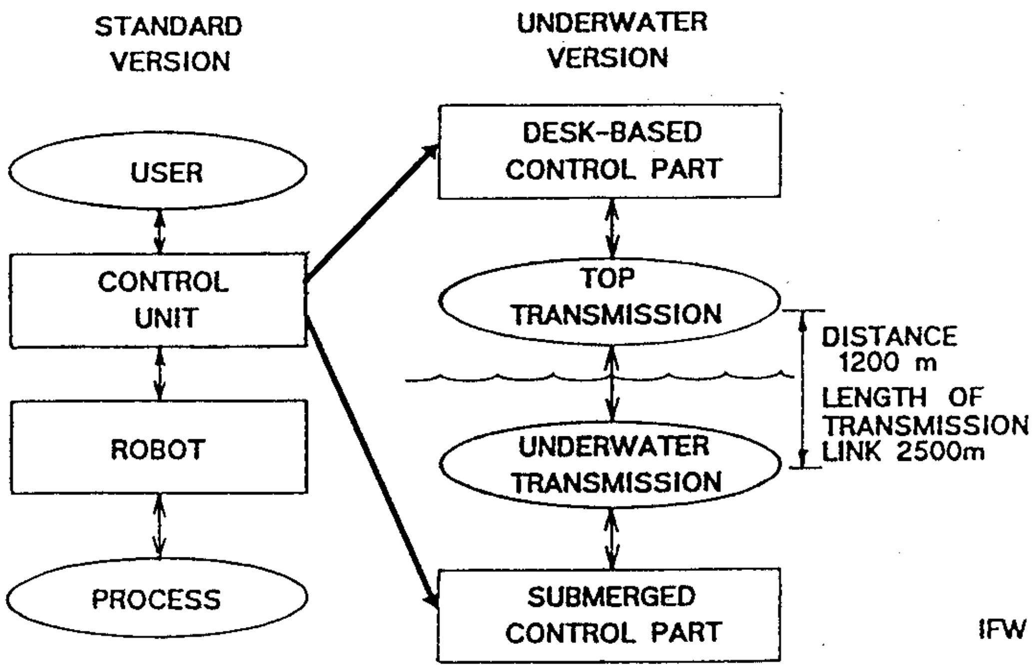
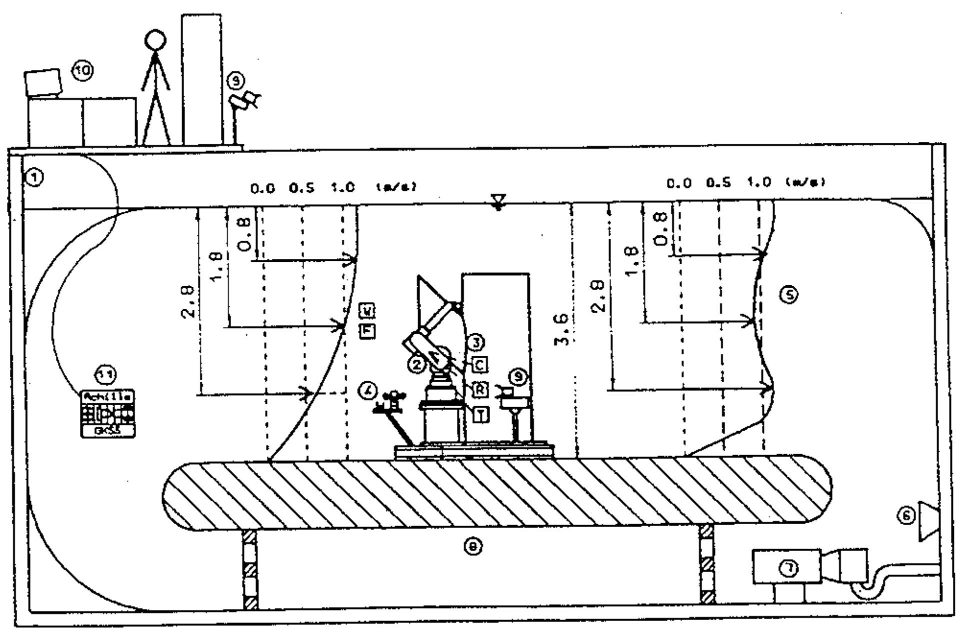


Figure 22 - Enhanced robot control system with a communication architecture configuration as required in underwater applications.



Equipment

1: jet pool
2: underwater robot r15 UW
3: node structure
4: tool changing device
5: profile of flow velocity
6: suction inlet
7: pressure nozzle
8: support construction
9: camera and light
10: control and measurement equipment
11: ROV "Achille"

Measurement

C: current
R: number of revolutions
T: temperature
W: water temperature
F: flow velocity

Figure 23 - Test arrangement in the jet pool.

Under these conditions the robot did follow exactly the pre-programmed path and working sequence. Continuous measurement of actuator currents, number of axes revolutions, different temperatures, pressures and volume control of the compensation system have been recorded.

During operation according to the test program it was proved a very safe and accurate function. The test program was accompanied by the GERMANISCHER LLOYD and at least all the results and some recommendations have been documented in a comprehensive certificate [60].

The tests of the accuracy of the robot end effector carried out under high pressure condition as well as under the maximum water flow velocity have shown, that the robot itself always kept an accuracy in repeatability of position, orientation and path of less than +/- 0.2 mm. Such very small values will be needed e.g. to perform precise work as the intended high pressure water jet cutting in the scope of underwater repair work. Actuators currents are strongly depending on the payload and on the flow resistance of the robot arms and the designed power is sufficient for a tool weight of 10kg and water current up to 1.1 m/s.

The Proposed Concepts for Diverless Pipeline Repairs

There are currently being considered for a diverless repair: robot/manipulator assisted orbital welding, and robotic welding.

Robot/manipulator assisted orbital welding

For this system it is necessary to design a habitat and a sub-sea module such that an orbital head and related equipment could be taken out and put back into storage and installed on the pipes by remotely controlled carriages and a manipulating arm. This manipulating arm is an 8-axis polar robot mounted in the roof of the sub-sea module and can be used to both install and service different equipment in the habitat. (see Fig. 24). The system consists of two task oriented set of components: pipe machining and pipe welding sub-systems. The former is composed by a tool orbital clamp which is primarily used to remove pipe ovality but also provides a rotating face plate which carries either the machine tools or the welding heads. The second element in this sub-system is a pipe machining tool which performs the following tasks: sawing, counterboring and bevelling of the pipe ends [42].

The pipe welding sub-system consists of two welding heads which can be installed on the rotating face plate of the tool orbital clamp, welding power sources, pre-heating and demagnetizing elements, a laser groove tracking and the weld control system. The latter uses a 383 Intel processor with sub-sea and surface control stations. It has been built for simultaneous hot, fill and cap passes with two weld heads [42].

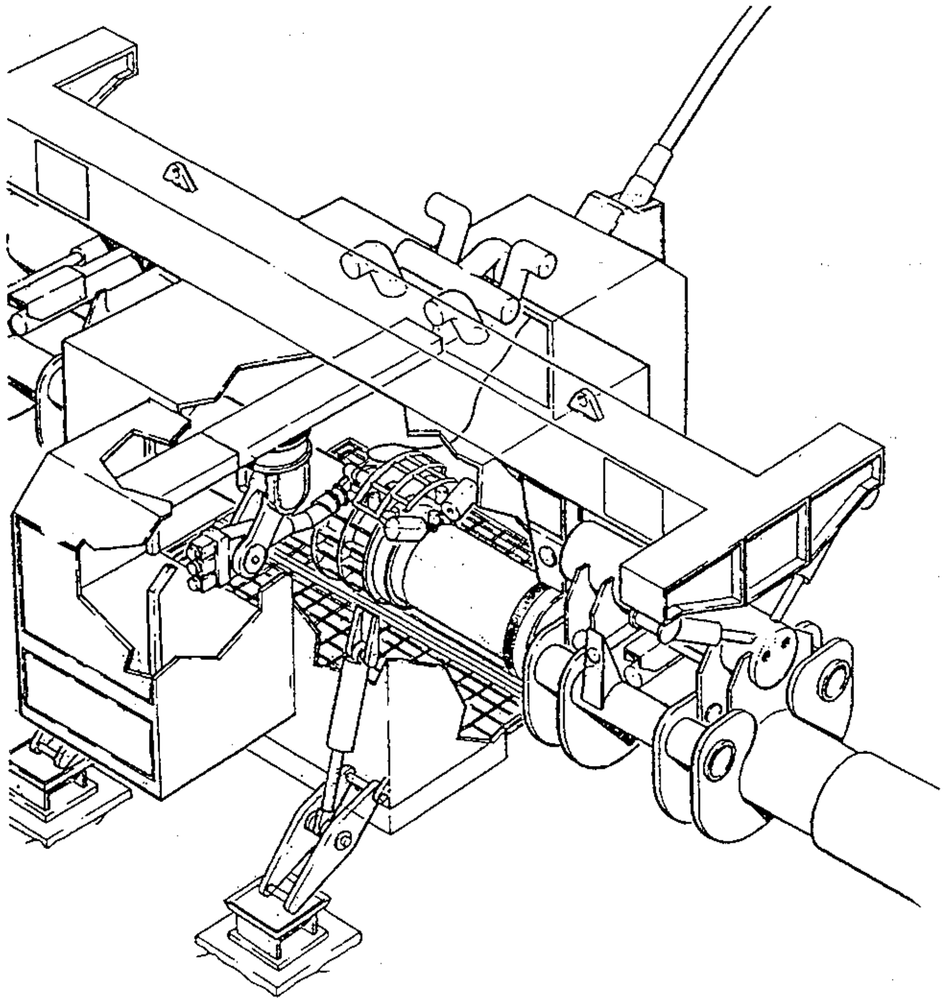


Figure 24 - Schematic view of a robot assisted unmanned orbital welding in an underwater habitat

This approach defines what is considered a "fast track" development which could provide a usable system in a relatively short period of time. Two further advantages of this approach would be the transfer of existing qualified welding procedures and the extensive use of existing equipment. The diverless equipment for preparatory work such as pipe preparation, alignment and habitat installation either already exists or is being developed.

Robotic welding system

This approach considers the use of robots and manipulators adapted to work under dry/wet hyperbaric conditions to perform the welding related. The preparatory tasks would be performed by diverless versions of already existing equipment.

The main element of such a system would be the underwater habitat. The habitat is a square shaped steel modular construction in which the bottom can be closed through sliding segments after installation over the pipeline. The side walls are designed with cut outs which surround the pipeline. A tight fit should be obtained through hydraulic operated covers. Such a construction guarantees the possibility to keep the internal top side of the habitat ~~dry during the tr~~ansfer from the surface to the sea bottom.

Further features of such a habitat are listed below (Fig. 25):

a) on the top of the habitat all penetrators and connectors for operation, control and monitoring tasks are mounted. A composite fibre optics and electric power umbilical system should fulfil the data transmission requirements and provide a back-up energy supply.

b) on the top of the habitat an additional connecting flanges are installed for the chamber and shielding gas supply necessary for the welding operations. The shielding gas storage can be mounted on a ROV. This ROV shall dock onto the habitat and therefore supply the required shielding gas. This procedure guarantees the exchange or renewal of gas supply according to the operational requirements (i.e., welding process employed) without interference with the remaining station components. Gas tanks, installed outside the habitat should supply additional chamber gas for the habitat.

c) two additional components should be an integral part of the habitat: the welding power source and an electrically driven hydraulic unit.

Inside the habitat the following systems are to be found (Figure 26):

a) two redundant robots are operated in the habitat. They are individually mounted on 180° semi-circular gantries in such a way that every position in the habitat can be reached. The robots are able to perform all necessary tasks (e.g., plugging, groove preparation, welding, testing, coating etc.). Both robots are controlled by a central computer. They can be independently or simultaneously operated.

b) at the bottom region of the side walls there are rail mounted manipulators,

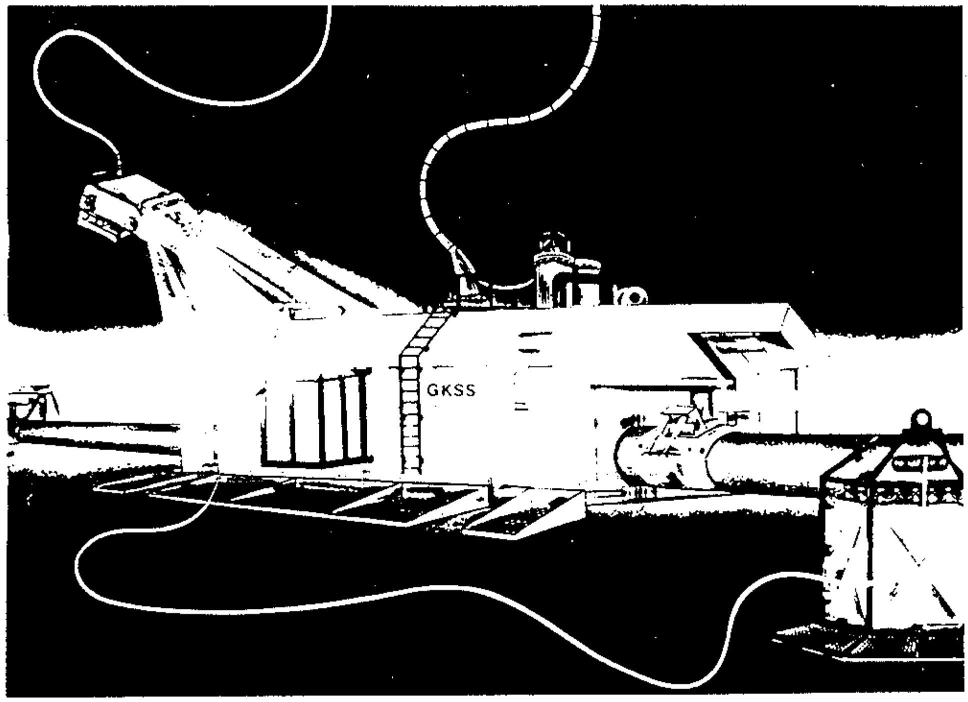


Figure 25 - Schematic view of a diverless repair station (habitat, alignment frames and subsea energy supply).

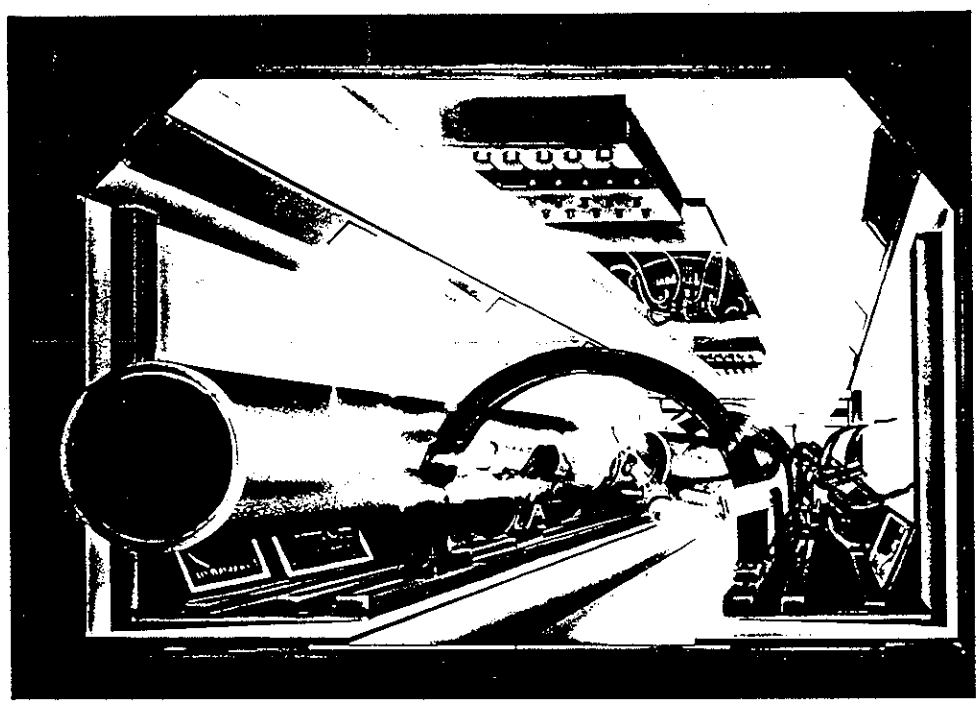


Figure 26 - Schematic view inside the underwater habitat. Pictured are two robots mounted on semi-circular gantries and two manipulators. On the habitat's ceiling there are two sets of tool magazines and the communication flange.

which assist the robots (in tasks such as, removal of the defective pipe section preheating, etc.)

c) special tools are stored in compartments (magazines) in the action radius of the robots or manipulators.

d) the spool piece or tap valve, pre-fabricated on the surface, is also located inside the habitat.

Approaches for a Robotic Pipeline Repair Procedure

Currently two repair alternatives are being considered, both being carried out as part of research projects sponsored by the European Union. The first alternative is based on a pipeline repair with the following steps:

- removal of the defective pipe section
- machining of a weld groove on the remaining pipe ends
- butt welding of the joint.

The second alternative, followed by a group of European and South-American partners, takes into account the removal of the defective region off the pipe (by a conventional underwater cutting process) and the welding of a sleeve over the defective region.

From a procedure point of view the basic difference between both alternatives is that the first one requires a root pass weld and the second one is based on fillet welds only. This difference in the repair approach can significantly affect the required development work to achieve a reliable underwater repair operation.

Presently all mechanized welding systems use the GTAW process with cold wire addition for the root run, which is not considered to be a robot-friendly technique. Although laboratory experiments have shown that it is possible to deposit root runs with the hyperbaric GMAW a significant amount of development work is still necessary to apply this process reliably. The deposition of fillet welds as proposed in the second repair approach would require a lot less development work since it involves a robot-friendly process (GMAW) operating in a less demanding weld configuration. However, the weldment properties might not attend the present requirements particularly, in the North Sea. It must be pointed out that the dimensioning of pipelines for greater water depths (below 600msw) is guided by the launching stresses rather then the operational conditions. In these circumstances a sleeve type of repair might represent an acceptable solution.

RECOMMENDATIONS FOR FUTURE WORK

Based on the state of the art in welding processes, mechanized and automated systems for underwater welding and the future needs of the offshore industry a series of research and development topics have been identified. These topics are listed below.

Welding Processes

(a) **SMAW**

- applicability of this process is limited by metallurgical reasons to 200 m,
- no immediate requirements for further R&D work,
- little information available on the effects of pressure on process behaviour.

(b) **GTAW**

- further R&D work required on process performance beyond 500 m, particularly considering:
  - → arc stability
  - → electrode performance
  - → arc ignition procedures
  - → evaluation of new shielding gas mixtures (Ar based)
  - → evaluation of process performance considering cold wire addition (arc stability, process efficiency and productivity)

(c) **GMAW**

- further R&D work required for applications beyond 500 m
  - → improvement of process behaviour (arc stability and metal transfer) considering:
    - • shielding gas composition
    - • out-of-position welding
  - → development of process control strategies for the short circuit transfer modes
  - → development of root pass procedures (based on a narrow gap joint configuration)
  - → evaluation of the behaviour of metal cored wires for this application (process and weld metal properties)

(d) **Plasma Arc Welding**

- development of process technology for multipass joints beyond 500m.

<u>Equipment</u>

(a) Improvement of torch design (GTAW, GMAW and Plasma) considering diverless applications.

(b) Development of sensors which could lead to the reliable diverless deposition of root runs, such as:

- seam tracking
- root run penetration control (i.e.: front face penetration control, weld pool oscillation frequency, etc.)
- de-magnetization

<u>Diverless Repair Technology</u>

(a) Fitness for purpose analysis of a diverless sleeve repair.

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Deepwater Applications

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As a reference to IIW DOC SCUW 124-90: "Standard Guidelines for Specifications for Underwater Welding" the following methodes for performing underwater welding are mentioned:

- welding in a dry one bar pressure vessel, independent of depth(one bar atmosphere welding),
- welding in a habitat at ambient pressure in dry condition, welders without diving equipment (dry habitat welding),
- welding at ambient pressure in a small gas filled enclosure, welders/operators in the water with diving equipment (dry spot welding)
- welding at ambient pressure, welders in the water, without a physical barrier between water and arc (wet welding).

The document mentions the following fusion welding processes to be applied or developed:

SMAW, GMAW, FCAW, GTAW, PAW.

In order to ensure the desired **process performance**, the effects of the hyperbaric environment such as pressure, humidity, high cooling rates on **quality** and **efficiency** of welding including operator performance are to be considered and implemented in more detailed and project orientated underwater welding specifications. The purpose of these guidelines is to serve to quality assurance and economy in underwater welding operations by providing a framework for it.

In assessing the various welding processes, the above mentioned key words can be interrelated by the following expression:

Process Performance = Quality of Welds + Efficiency of Welding

with: Quality = Soundness + Joint Material Properties
Efficiency = Load bearing Weld Joint Area produced per Unit Time per Cost of Equipment and Work Force including NDT

For a quantitative assessment the following questions and respective answers are to be discussed:

1. What are the effects of arc and pool stability on process performance?

Arc stability has been defined by the following :

- blow out
- short arcing
- axial and radial arc displacements
- secondary arcing
- voltage spiking
- anode/cathode spot displacements

as affected by magnetism, pressure, shielding gas turbulence, unstable droplet transfer instable TIG electrode tip molten pools, reduced excess pressure at hyperbaric PAW.

Pool stability is mainly related to weld pool behavior in positional welding. It is generally considered as unsatisfactory in cases where excessive weld root reinforcement or droplet formation is observed or excessive reinforcement in the overhead position is providing unsatisfactory weld geometries.

Control strategies have been worked out by application of:

- pulsing
- adapted welding parmeters at orbital positions
- additional magnetic fields
- optimized filler wires
- power source characteristics including adapted current response rates and open circuit voltages,(IIW DOC -SCUW 139-92)
- optimized shielding gas compositions

2. What is the mechanism and the effect of gas contaminants pick up in the weld metal at hyperbaric conditions?

The following effects have been considered:

- ambient pressure at constant partial pressure of gas contaminants
- partial pressures of contaminants at constant ambient pressure
- welding parameters including pulsing and orbital positions
- arc stability
- polarity
- ionizing elements

- weld bead geometries including thickness and thermal properties of material

The specific effects are to be considered separately for consistent conclusions. It is understood that, for instance, the general increase of contaminating gases in the weld metal at increased ambient pressure is observed at large partial pressures of those elements in the arc atmosphere, which, at one bar, would create excessive porosity.

3.What effect has the hyperbaric environment on quality including soundness from defects and material properties?

The following effects are of importance:

- ambient pressure on penetration and fusion of side walls,see
- arc stability
- oxygen on burn off of Si,Mn,Al,behavior of C,including inclusions and microstructure
- nitrogen on mechanical and corrosion properties (Duplex Stainless Steels)
- hydrogen on delayed cracking with respect to CE levels, welding parameters, layer techniques, filler metal chemistry, restraint intensity including weld joint configuration,work piece temperature regime, in particular, at wet welding procedures.

In this aspect, the following recommendations have been given by the working group :

Recommendation No. 1:

For the extension of wet welding into deeper water and more challenging environments, a consistent documentation of recently performed wet welds and their service behavior should be carried out. This should be documented by:

- type of electrodes
- layer technique
- joint type including plate thickness and edge preparation
- position
- heat treatment
- NDT results
- qualification testing
- service time
- service load spectrum including corrosion

Recommendation No. 2:

For verification of service behavior of wet welds in more challenging environments and deeper water, backing up fatigue tests in sea water under realistic loading conditions should be performed .

Recommendation No. 3:

For consistent demonstration of effective crack avoiding wet welding techniques, modelling of hydrogen diffusion profiles by FEM calculations including temperature profiles of actual joint configurations should be carried out providing required measures for efficient reduction of local hydrogen in crack critical areas with respect to microstructures and local stress /strain.

The following further items have been evaluated:

4. Requirements for automatization at depths > 350 msw

It was concluded from the discussion,that due to recently taken decisions for development of respective deep water oil/gas reservoirs, there is an urgent need for advanced development of deepwater automatization of joining and testing methods. Such methods are based on the use of advanced ROV facilities and should be consistent with them.

Also, the possible limits of the presently used fusion welding processes with increasing water depth are to be verified. Solid phase processes have to be considered and evaluated from the point of feasibility.

The working group recommends as follows:

Recommendation No. 4:

As a consequence of reduced physical abilities of divers below 500 msw, the verification of quality of hyperbaric weld joints beyond this depth may be achieved by either automated NDT systems or suitable online process control. R&D work on both methods is recommended to be carried out. The following processes may be suited for on line process control: FCAW, GMAW, GTAW, and PAW. In particular,the solid phase joining processes as for instance,friction,flash butt,shielded active gas (SAG) should be considered, since they are less sensitive to depth effects.

For the conventional fusion welding processes, the following developments might be pushed forward:

- narrow gap welding or welding without filler wire
- seam tracking and arc sensing devices

- arc voltage and video imaging ,
- penetration control on line by available methods as proposed in the literature.

5. Potential of new materials, other than mild steel

The following materials have been considered for their performance in the offshore environment and for deep underwater welding:

- Duplex Stainless Steels (North sea)
- Martensitic low Carbon Stainless Steels
- Cladd Steels
- Titanium Alloys
- Ni base Alloys

Their application to subsea production systems and respective pipe systems is under development and requires close attention. Since the corrosion aspect is the main reason for their increasing use, the effects of hyperbaric welding on corrosion properties are to be focussed on.

Advanced Technology and Challenges in Underwater Welding

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Abstract

This paper reviews the existing limitations and future challenges associated with underwater welding. The paper includes a detailed review of the current research and development programs involving underwater welding. In addition, the paper summarizes the results and conclusions obtained from extended Working Group discussions in which future underwater welding research and development needs were reviewed and discussed. The results of the discussions are summarized in table form in which each welding process/technique is assessed in terms of the following parameters/characteristics:

- Environment (wet or dry)
- Depth limit
- Range of applications (new construction or repair, joint geometries, etc.)
- Range of materials amenable to process/technique
- Process characteristics
- Development cost
- Risk (technical and economic)
- Development time.

The review covers the following welding processes/techniques:

- Arc welding (activated GTAW and microwave plasma)
- Laser welding (CO_2, YAG, and combined arc and laser)
- Electron beam welding
- Resistance welding (flash butt and homopolar)
- Friction welding (conventional, radial, taper stitch, and FHPP)
- Explosive welding (bell and spigot and sleeve/patch).

Introduction

Underwater welding, both wet and hyperbaric, has become a well developed art that is being used successfully for repair of marine structures and, to a limited extent, for original construction. However, as with surface welding, the art must transition into a science for welding to reach the level of reliability needed to become a universally accepted fabrication process.

Significant advances must be made to achieve the goals that are being set for underwater welding, and these advances must be made with a planned, scientific approach. While some past investigations have been interesting and some of the results reasonably successful, they were frequently undertaken without a full understanding of the total welding environment. The total welding environment includes the working environment immediately surrounding the welding site, the working requirements of the welder/diver, the service requirements of the completed welds, the physical and mental requirements for the welder/diver, effects of the environment on the welding process, etc.

Conventional and common surface welding processes have been the processes of choice for underwater welding. These have been the arc welding processes with manual shielded metal-arc (SMA) welding the favorite. There is good reason for this choice since SMA is simple, requires no specialized equipment, and is widely used on the surface so there is a familiarity associated with such welding, and since consumables are widely available. However, there is a menu of other welding processes that have potential for underwater applications. some of which have already been investigated to a limited degree. For this discussion, these latter processes have been designated "advanced processes."

The general thinking to date has been to adapt and use arc welding for all underwater welding operations regardless of depth, service requirements, or structure design. The goal is to have a welding process that is capable of making permanent repairs to structural members of marine structures. For maritime and naval structures, repairs are confirmed to less than 50 ft. (15 m)[1]. In such cases wet welding is a viable option. For offshore structures, the depths can be significantly greater. Two approaches have been taken for making repair welds at these greater depths. North American companies have concentrated on the development of wet welding while European companies have been developing dry welding in a hyperbaric chamber. Each approach has its supporters, and there are valid arguments for both approaches.

Although wet welding procedures have been qualified down to depths of approximately 100 m (300 ft.), there is still some reluctance, particularly in Europe, to use wet welding for structural repairs. Indeed, in Europe wet welding procedures have to date only been qualified down to depths of approximately 50 m (165 ft.). Hyperbaric (dry) welding procedures, on the other hand, have been qualified down to depths in excess of 500 m (1650 ft.).

In addition to considering depth limits for weld procedure qualification (i.e., the ability to fabricate sound welds with acceptable microstructural and mechanical properties), it is also important to consider diver/diving limitations. For depths less than approximately 50 m (165 ft.) divers can bounce dive breathing air, although manual decompression needs to be exercised for depths greater than approximately 10 m (30 ft.). At depths greater than 50 m (165 ft.) divers breathe mixed gas instead of air due to the narcotic effects of nitrogen at depths below 50 m (165 ft.). In general mixed gas is obtained by adding helium to breathing gas. At depths below 50 m (165 ft.), saturation diving is commonplace with divers spending extended periods of time

[1]Conversions between English and metric units in this report are approximate since the discussions are general and exact conversions are not necessary.

in pressurized chambers. Nevertheless, even with the advent of mixed breathing gases, the physiological and health risks increase with diving depths. These increased problems and risks result in a depth limit for divers of approximately 500 m (1650 ft.), i.e., divers should not spend extended periods at depths greater than 500 m (1650 ft.). For depths greater than 500 m (1650 ft.), diverless welding systems or systems that provide the diver with a sheltered environment, [e.g., a pressurized environment (submarine)] are the only viable options.

Generally, the quality of wet welds does not meet the requirements of surface welds and is limited to permanent repairs in non-structural members in redundant structures. Current development efforts are being directed to achieving surface weld quality. The advantage wet welding holds is that it is less costly, can be done relatively rapidly, and does not require specialized supporting equipment. Welding in the dry atmosphere of a hyperbaric chamber can achieve surface weld quality but the operation is more costly and requires more time, supporting personnel, and equipment.

For arc welding, the depth effects have been particularly difficult to address. With depth, arc characteristics change, the arc constricts, electric parameters change significantly, the gas shielding bubble shrinks (wet welding), chemical reactions change, cooling rates change, etc. In short, arc welding becomes extremely complex when all of the pressure effects are considered. For this reason, serious consideration should be given to other welding processes for which the pressure effects are minimal or that do not require an arc or perhaps even melting to achieve an acceptable weld. One can visualize the use of arc welding to a specific depth, e.g., 670 ft. (200 m), above which the pressure effects on the arc are relatively mild and easily overcome. Below this depth, welding would utilize a different process--one which has little sensitivity to depth or with which the depth effects can be readily handled.

The discussion of welding processes that follows summarizes the recent and ongoing developments in both conventional arc welding processes for wet welding and non-arc processes and variations of arc processes that could potentially be considered for underwater welding because of their process characteristics, particularly their insensitivity to pressure effects.

Developments in Underwater Wet Welding Technology

The arc-welding processes are the common processes used for wet welding, chief among these being shielded metal-arc (SMA) welding. Other arc-welding processes have been investigated for wet welding but, to date, none have been able to produce the quality of SMA welds without significant shortcomings. However, continuing development of the other arc-welding processes could result in a process that meets the quality of an SMA weld plus significant improvements in weld speed, consistent quality, ease of use, and equipment reliability.

Shielded Metal-Arc Welding

The SMA (manual welding with covered electrodes) process is the "universal" process for wet welding and is used extensively for hyperbaric welding. Because of its simplicity and the extensive bank of experience, this has become the most advanced underwater wet welding process.

It also is the logical process for which further advancements are being made. These advancements are in the form of improved electrode coverings and weld metal compositions and of process modifications that enhance the operating characteristics of the electrodes, the quality of the deposited weld, and weld joint properties.

Global Diving and the Colorado School of Mines are currently undertaking a program to develop flux (electrode covering) formulations for ferritic electrodes to provide improved weld joint properties when used in combination with temper-bead welding techniques. Wet welds have been made in ASTM A36 steel that have passed the requirements for AWS D3.6 Type A welds. Similar welds were made in A537 Class 1 steel having a carbon equivalent of 0.46 that met all of the A3.6 requirements except that some of the bend tests met the Type B rather than the Type A bend test requirements.

The temper bead technique when properly applied prevents the formation of hydrogen cracks by softening the heat-affected zone (HAZ) to a level that the hydrogen will not create cracks. Proper application of temper beads includes rather precise placement of the beads which, in turn, requires additional welder skill and training. These techniques have been developed successfully for use with above-water welds made on flowing gas and liquid pipelines, particularly for hot tap welds. Welds on flowing lines can cool extremely rapidly due to the cooling effects of the flowing contents. Very hard HAZs can result that are susceptible to hydrogen cracking either during the welding operation or later in service. Detailed procedures have been developed for using temper beads to soften the welds; these procedures have been proved and qualified for production field hot taps and should prove successful for wet welding.

The timing of the application of the temper beads is very important. Hydrogen cracks start as microcracks that form very quickly after solidification of the weld metal and grow as the weld cools or during the immediate period (24-48 hours) following the welding operation. The temper bead should be deposited before the microcracks begin to form. Special electrodes are available commercially that are specifically intended for making temper beads on above-water welds. These electrodes are not consumed and do not deposit any metal--they merely apply heat so the welder does not have to control any additional molten metal. Limited evaluations of such electrodes for underwater application have been made, and the preliminary results are promising.

The U.S. Navy has been developing a nickel-base electrode for making permanent non-structural repairs to ship hulls. Because of this particular application, the maximum depth of interest is 35 ft. (10.5 m). This electrode is a commercially available nickel-base electrode that has been waterproofed with a proprietary coating. Welding evaluation tests of this electrode currently are being conducted in open sea water. The results obtained to date are promising. Because of the Navy's depth limitations vis-a-vis those of the offshore industry, the perennial shortcoming of nickel-base electrodes, i.e., the formation of gross porosity at depths below 50 ft. (15 m), has been avoided. The nickel electrodes do operate differently than ferritic electrodes--the molten weld metal is more viscous and sluggish and the slag is more adherent, so grinding is the only satisfactory method of slag removal.

Another electrode development program that is receiving some Navy interest is being conducted at The Ohio State University. This electrode is ferritic and has a special flux covering that provides good operability, very easy slag removal, and very low porosity compared to conventional E7013 electrodes. Tests on DH36 hull steel currently are being made in 35 ft. (10.5 m) of water in a quarry.

A development program conducted by Southwest Research Institute took a somewhat different approach by using a flux-cored covered electrode. The composition of the flux core was varied to provide different electrode (and weld metal) compositions. The composition of the core material can be altered more readily than can that of the extruded covering, so a variety of flux compositions can be evaluated more cheaply and quickly than if all variations were made in the extruded covering. The results were promising with the welds made at depths of 34 to 300 ft. (10 to 90 m) having good properties, particularly impact properties. Although the welds met A3.6 Type A soundness requirements, microfissures were detected at magnifications of 300X-500X. Their length was in the range of 0.002-0.010 in. (0.05 to 0.25 mm) but they did not seem to create problems with fatigue, bend or tensile properties. The quantity seemed to be related to the manganese/silicon content of the weld metal and may have been caused by hydrogen, but there was no proof of this.

Flux-Cored-Wire Arc Welding (FCAW)

Gas metal-arc (GMA) welding uses a continuous solid wire electrode that is fed from a spool or reel with the arc being shielded by a gas envelope that is created by an auxiliary gas supply. A common variation of this process uses a flux-cored wire that may be designed to generate its own shielding gas from components of the flux core. The major advantages of any GMA process are that it is continuous with no interruptions to change electrodes, there are no stub losses, and the arc parameters are controlled automatically. By using a self-shielding flux-cored electrode, the complexity of supplying the auxiliary gas shield is eliminated. This is an attractive process for underwater welding as it is more efficient and faster than SMA welding and the electrode can be readily customized for wet welding at specific depths as with the flux-cored covered electrodes developed on the Southwest Research Institute program.

This welding process uses a constant-potential power supply and the wire is fed at a constant predetermined rate. The power supply automatically changes the welding current to maintain a preset arc voltage (arc length). Thus, the welder does not have to manipulate the electrode to maintain the desired arc length; he needs only to guide the arc along the joint. This characteristic of FCAW may be a disadvantage for wet welding as the welder cannot "feel" the weld joint by holding the electrode against the joint side. Some other means of guidance may have to be devised for manual FCAW.

A self-shielded flux-cored electrode wire has been developed by the Electric Power Research Institute (EPRI) for making wet weld repairs to nuclear reactor components. Procedures for making such repairs by the SMA process have been developed and used successfully for more than two dozen repair operations worldwide. However, the desire to minimize diver exposure time to radiation led to the development of the FCAW electrode and process for reactor repair. The reactor components are fabricated from austenitic stainless steel or nickel-base alloys. Therefore, the flux-cored wires are of similar composition. While electrodes of these compositions may not be desired for welding ferritic steels, the technology for developing self-shielding flux could be applied to an electrode producing a ferritic weld metal. As with SMA welding, hydrogen pickup remains a problem with FCAW although the nickel-base electrode might provide a solution. The successful use of these wires and this welding process also required modifications of the welding power supply as noted in the section "Welding Power Supplies."

Another self-shielded flux-cored wire for welding ferritic steel and the supporting wire feeding equipment have been developed by the Paton Welding Institute in Kiev, Ukraine. The wire feeding equipment is contained in a suitcase size container that is not sealed; thus, the wire drive equipment and the reel of wire are exposed to sea water at the depth pressure. The first demonstration of this system in the U.S. was less than satisfactory but subsequent improvements have been directed at overcoming the problems that were encountered.

Flux-cored wires have been used very successfully for surface welding and have received wide acceptance in production. Their advantages warrant further investigation for underwater wet welding. The requirement for wire feeding equipment would tend to limit its application; it definitely would not totally replace SMA welding but once the full capabilities of FCAW are determined, its position in underwater welding then could be established.

Arc Welding Power Supplies

For wet welding, a switch from motor-generator to inverter type power supplies is being made. The inverter power supplies are much smaller and lighter weight and provide a more stable and controllable arc. This probably is due, in part, to the very fast reaction time of the inverter power supply to momentary changes in arc length (arc voltage) caused by transfer of metal droplets from the electrode end or by position changes made by the welder.

If arc welding is to be adapted for deep water welding, power supply development will be required. Even for the lower depths of shallow water welding, power supply modifications could be useful. The need to maintain an arc at high pressures really should involve the development of a power supply having machine characteristics tailored to the pressure regime in which the arc must operate [Ref. 1]. An effort akin to this was part of the EPRI flux-core electrode development program. Several commercial solid-state power supplies were investigated but none had the desired machine characteristics even for welding at 25 ft. (7.5 m). Modifications were made to one of these power supplies to provide the machine characteristics needed to maintain the arc characteristics that would produce a sound weld.

Both Cranfield University in the UK and the GKSS Research Center in Germany have conducted preliminary investigations of power supplies aimed at the ultimate development of a power supply tailored for underwater welding [Ref. 2 and 3]. Both investigations centered on the inverter-type power supply and involved wet-welding trials. The Cranfield effort utilized a computer control of the inverter power supply with the current and voltage operating levels, the slope characteristics and dynamic response being controlled by the computer. This preliminary work was limited to a water depth of 10 ft. (3.3 m), but significant improvement in arc operation was achieved.

Advanced Welding Processes

All of the welding processes discussed in this section are or should be relatively insensitive to the higher pressures of extended depths. The lack of pressure effects has not been proven for all candidate processes, but experience with above-water welding suggest that pressure may not be a major factor. The processes also must be considered from the standpoints of wet or dry application, the cost and time required to develop the process for underwater use, the technical and economic risk related to successful development of the process, as well as other characteristics distinctive to the individual processes. These characteristics are covered in the sections on the individual processes and are summarized in Table 1.

Three depth limits are noted in this table: 500, 1000 and greater than 1000 m (1650, 3300 and greater than 3300 ft.). The 500 m limit is the current maximum depth at which arc welding can be performed. The next limit, 1000 m (3300 ft.), is twice the first limit and indicates that pressure has some effect on the process, but it would be workable far deeper than the best current arc welding processes. The process must also be capable of remote operation since this is beyond a diver's limited working depth. The third limit indicates that pressure should have no effect on the process and it probably could be used at any depth desired.

"Applications" refers to the type of joint that can be welded. The materials that are considered are steel alloys including stainless steels, titanium alloys, aluminum alloys and clad materials. The advantages and disadvantages are those that would be considered significant to the selection of a particular process. No specific values are given for the development costs, but they are considered to develop the process from its current status to actual application in underwater welding. The technical and economic risks rate the possibility of technical success and the related risk of recovering development costs. The three development time periods are short (1-3 years), medium (3-5 years), and long term (5-10 years).

Arc Welding

While conventional arc welding is very sensitive to the operating depth, there are two arc welding variations that probably will be significantly less depth sensitive. These are "activated" gas tungsten-arc (GTA) welding and plasma welding.

Activated GTA Welding. The gas tungsten-arc process is widely used for the high quality welding of alloy steels, aluminum, and titanium. The process has relatively low heat input, welding speed, and shallow weld penetration. Penetration can be improved significantly by applying a coating on the joint surface prior to welding. The coating is a liquid suspension of various compounds that are vaporized by the arc and act to greatly improve weld penetration. The exact mechanism by which the penetration is increased still is under study but is believed to be related to several factors, either individually or in combination. These include improved arc stability, increased emissivity of the tungsten electrode, change in the flow pattern, and/or the fluidity of the molten weld metal [Ref. 4]. This behavior has been demonstrated in the welding of carbon steels, stainless steels, and nickel-copper alloys. Penetration in material thicknesses of interest for underwater structures can be doubled depending on the material being welded.

The application of this technique underwater could reduce welding times and shorten the entire welding operation. If the arc behavior is improved by these surface coatings, the process may be found to be less depth sensitive and the water depths at which GTA welding could be used could be increased. The process still would be restricted to dry chamber welding.

Plasma Welding. One of the effects of high pressure on a welding arc is to constrict the arc into a narrower column. This effect would be minimized in plasma-arc welding as the arc already is constricted. This constriction is done to create a more efficient heat source to allow higher welding speeds and deeper penetration. Investigations have and are being conducted on the use of plasma-arc for both wet and hyperbaric chamber welding.

In the conventional process, the plasma is generated by an arc maintained between a tungsten electrode and the work piece. At high hyperbaric pressures, the voltage must be increased to maintain this arc. This results in higher electrode temperatures with some melting of the electrode and the high-speed flow of the plasma gas around the electrode erodes the electrode tip, resulting in relatively short electrode life.

Investigators at TWI, Cambridge, UK, have been investigating generation of the plasma by microwaves [Ref. 5]. This technique eliminates the tungsten electrode with its problems of erosion and replacement (which is awkward even above water). If this technique is successful, there could be significant advantages for underwater welding although it probably would be restricted to dry welding, at least initially.

The welding torch should be less bulky and the need for high open circuit voltage to initiate the plasma arc would be eliminated along with the safety hazard associated with high open circuit voltages in wet welding. The process would retain its probable insensitivity to depth. The cost to further develop microwave plasma for underwater use should be relatively low and require probably 3 to 5 years of further development effort.

For wet welding, a gas cavity must be maintained around the plasma jet to insure its stability. Several investigations have involved methods for creating this gas cavity. These devices are bulky and interfere with observation of the welding process. At extended depths, welding would be mechanized rather than manual so these devices may not be too bothersome. A supply of both plasma gas and a gas to maintain the cavity surrounding the plasma jet is needed. This is a complication that may overshadow the higher welding speed and penetration that are characteristic of plasma welding. In addition, some hydrogen will be present in the plasma jet atmosphere in wet welding and the weld will cool rapidly. Thus, hydrogen cracking of the HAZ may be a problem with wet plasma-arc welding as it is in conventional arc welding.

Although plasma welding can be performed manually, the process probably would be mechanized for underwater application, either wet or dry. Plasma welding is far less sensitive to the torch-to-work distance, so mechanization would be simpler than for conventional arc welding.

Laser Welding

With the advent of high-power continuous-wave lasers, laser welding is taking its place in industrial welding operations, particularly in the automotive industry. It is characterized by very high concentrations of energy in the weld area and the ability to direct the laser beam into areas that are geometrically awkward. It is applicable to the welding of butt, lap, fillet, and tee joints. Laser welding has the potential for both wet and dry underwater application.

Pressure certainly will not affect the laser beam. There may be a need for a supplemental gas envelope to keep the beam from contact with the water for wet welding. Initial investigations using a CO_2 laser in water showed that some of the energy of the laser beam is absorbed by the water, creating a steam channel surrounding the beam. The absorbtivity of laser light by a material is related to the wave length of the beam. Beams of other wavelengths such as from a solid-state laser may not be absorbed to the degree necessary to create this steam channel. A program on wet laser welding just starting at the Penn State Applied Research Laboratory will be using a YAG laser, which produces a different wave length. The formation of the steam channel will be one of the first items investigated. Of course, dry chamber welding will not have to cope with this problem.

The significance of this steam channel also must be investigated. Will it create problems? Will the water vapor in this channel be dissociated by the laser beam to create a hydrogen problem? If hydrogen is a potential problem, then some means of keeping the water from the laser beam must be devised.

The beam can be directed to and traversed over the welding area optically, although supplemental mechanized devices also are required. The beam is transmitted optically to the welding site so the laser does not have to be located exactly at the welding site. The distance that a beam can be transmitted is about 50 ft. (15 m) for a CO_2 laser using mirror systems for transmitting the beam. Because of its different wavelength, the beam from a YAG laser can be transmitted through a fiber optic system and the maximum transmission distance by this means is about 500 ft. (150 m).

Current high-power lasers, particularly the CO_2 lasers, are bulky and sensitive to rough handling and would be almost impossible to locate under water for welding at depths greater than the maximum transmission distance. Since the beam from a solid-state laser can be transmitted greater distances, the solid-state laser could be located topside and the beam transmitted to the welding site. For welding at depths greater than the maximum beam transmission distance, the solid-state laser could probably be adapted to an underwater location as these lasers are relatively compact and could probably sustain the bumps and bangs of handling and transporting to the underwater location.

The laser beam is focused to a very small diameter to achieve the very high concentration of energy to make the weld and obtain deep penetration. Because of this very small diameter, tracking of the joint and the joint preparation are critical. Laser welding must be mechanized to obtain accurate joint tracking to avoid wandering from the joint with resulting areas of lack-of-fusion. Similarly, the joint must be carefully prepared (machined) and fit up, again to avoid lack of fusion. The maximum joint gap that is permissible is in the order of three percent of the joint thickness.

In a variation of this process, laser and GTA welding have been combined for welding long butt joints in sheet steel at high travel speeds [Ref. 6]. A GTA welding arc becomes more unstable and harder to control as the travel speed is increased above certain levels. By impinging a laser beam immediately ahead of the arc, some of the laser vaporized metal enters the arc atmosphere and acts to improve arc stability and allow increases of travel speed by an order of magnitude. A similar arrangement of laser and arc might improve arc stability at high pressures and improve arc operability for welding at extended water depths. Such a combination might be practical only for dry welding, but it is a technique that merits further investigation in combination with the GMA and FCA welding process as well as the GTA process.

Electron-Beam Welding

Electric-beam (EB) welding is an intriguing process because of the very high depth-to-width ratios obtainable in EB welds, the impressive penetrating capabilities of the beam, and the high travel speeds that the process can achieve. This process normally is mechanized because of the necessity of welding in a vacuum and the precise guidance along the joint that must be done because of the very narrow beam. Although equipment has been developed for out-of-vacuum welding, the electron beam diffuses rapidly as the electrons collide with air or shielding gas molecules; thus the electron gun must be positioned close to the work piece so the beam will impact with the joint before it diffuses significantly. A diffused beam lacks the energy concentration necessary to obtain the deep penetrations characteristic of EB welds. If the gun-to-work distance is too great, the diffused beam may lack the energy concentration necessary to even make a successful weld. Even when positioned properly, the depth-to-width ratios of an in-air EB weld will be significantly lower than for a weld made in a vacuum.

A manual EB welding gun was developed by the Paton Welding Institute in Kiev for welding in space. The vacuum of space is better than the vacuum of EB welding chambers because there is no problem of beam diffusion. Reportedly, this system performed very well in experiments conducted in space by cosmonauts and may have been used in the construction of the Russian space station Mir. One of the hazards of EB welding is the generation of hard X-rays when the electron beam impacts the metal work piece. These X-rays have enough power to be lethal unless lead shielding is used around the immediate area of the welding. Such shields apparently have been successfully developed as the space EB welding guns were hand held and there have been no reported hazards to personnel.

This portable EB welding system could be attractive for dry underwater welding as it can be used for welding any metal of interest for underwater use, it can make welds rapidly, and the welds are of very high quality. However, the portable system was designed for vacuum operation and with the present state-of-the-art, a vacuum environment cannot be utilized practically in underwater dry chamber welding. For dry chamber use, welding must be in-air and, as noted above, in-air EB welding loses some of the advantageous characteristics of vacuum EB welding. In addition, at higher pressures, the air through which the beam must traverse before impacting on the work piece will be denser and the beam will diffuse more rapidly and in a shorter distance. Thus, the EB welding process will become depth sensitive and pressures will be reached at which satisfactory performance may not be achievable.

In addition to these welding atmosphere considerations, there are some other deterrents to underwater EB welding. The equipment is expensive and is not adapted to the rigors and rough handling that it would experience in underwater use. Because of the narrow weld that is produced, the preparation of a butt joint is critical, although the in-air welds are wider than in-vacuum welds. (For a lap joint, such precise tracking would not be required as usually there would be no exact joint location that would have to be followed.) Still, the joint faces must fit closely and must be machined carefully to achieve a weld that is without voids or unwelded portions. Similarly, the butt joint must be tracked precisely to avoid displacement of the beam to the side of the joint, which again would result of unwelded areas. If the welding operation would be mechanized, better tracking could be obtained and perhaps a localized vacuum or low-pressure enclosure could be positioned to surround the welding area with a suitable atmosphere for welding.

Flash-Butt Welding

Flash-butt welding has been used for many years for welding bar and tubular products end-to-end. With few exceptions, this operation is done in a fabrication plant setting because of the large size and weight of the equipment and the need for large amounts of electric power. Equipment and techniques for field welding of large-diameter transmission pipelines were developed in the former USSR for use in Siberia. Subsequently, the process was developed for lay barge use by McDermott, Inc., in the U.S. Underwater applications probably would be limited to the welding of pipe or tubing.

This is a one-shot process that will make a weld in 24 in. (600 mm) diameter pipe in about 1-1/2 minutes not including equipment set-up time. A flash-butt weld is a solid state weld. No filler material is required as there are no consumables related to the process and no shielding gases are required except in the welding of titanium.

The welding heat is produced by arcing between the joint faces; after a predetermined arcing period, arcing is discontinued and the hot joint faces are forced together by axial loading. This forging operation extrudes any foreign material, molten metal, and hot, plastic metal from the joint and a solid state or forge weld between the parts results. After the weld is completed, the metal that is extruded from the joint (flash) must be removed by grinding or some form of machining. If the pipe material is hardenable, a post welding annealing or tempering treatment must be used to soften the HAZ. This can be done by applying a low current electrical pulse from the welding unit or by induction heating.

Two types of welding equipment have been developed. For small diameter pipes, the welding equipment is clamped onto the outside of the pipe; for diameters greater than about 24 in. (600 mm), internal machines have been developed. The equipment, either external or internal, is bulky and heavy. The McDermott internal system for welding 28 to 36 in. (700 to 900 mm) diameter pipe weighed about 46,000 lbs (20,900 kgm). Alternating welding current is supplied from a step-down transformer incorporated into the welding head. In turn, the transformer is supplied from diesel powered generators; the size and number depending on the welding current requirement. The McDermott equipment for welding 28 to 36 in. (700 to 900 mm) diameter pipe used a 1000 kw generator. Either pneumatic or hydraulic equipment is used to apply the forging force to the heated weld joint.

For underwater application, the process probably would be used in a dry habitat. For wet welding there would be several problems to overcome. The equipment would have to be designed to operate in a water environment, and the presence of water at the joint interface might affect the initiation and operation of the flashing arc. Steam would be generated in the joint gap during the flashing action, and hydrogen would be generated by the flashing arcs just as in conventional arc welding and would diffuse into the hot base metal. A post-weld tempering operation could drive the hydrogen from the HAZ and soften the HAZ microstructure but it would have to be applied immediately after the weld was completed. In a dry environment, the main concern would be containing the sparks and material expelled during welding. Divers probably would have to exit the chamber for safety reasons during welding. This probably would not be a problem as the equipment is mechanized and welding could be conducted remotely. The equipment could also be designed for remote placement.

For either wet or dry application, the effects of pressure must be determined. Although the hyperbaric pressure would have some effects on the arc, this may not be a significant problem as the arcs in flash welding are not as "sophisticated" as conventional welding arcs, and these effects may not have a significance on the quality of the weld or on the welding operation. If they do, these effects may be overcome relatively easily.

Homopolar Pulse Welding

Homopolar pulse (HP) welding is a variation of upset butt welding (one-shot solid-state process) that uses a homopolar pulse generator as the power supply. This generator supplies a high-current, low-voltage electrical pulse in a very short time. Typical pulse parameters are 500 kiloamps at 20 volts delivered in a pulse duration of 3 seconds. The butted ends of the parts being welded are heated very rapidly to the welding temperature, at which time the upsetting force is applied and a solid-state forge weld is accomplished. Contact between the joint faces is maintained throughout the heating cycle. No arcing occurs as in flash-butt welding, so there should be no problem with hydrogen generation and pickup.

The homopolar generator has a rotor that rotates at a predetermined speed. The electrical pulse is generated by activating a surrounding magnetic field and engaging brushes that slide on the generators slip rings. The current flows into two sets of electrodes that are attached to the ends of the parts near the interface between the parts.

HP welding is being examined in a current 5-year program for welding pipe for a J-lay operation [Ref. 7]. To date, only small diameter [3 in. (75 mm)] pipe is being welded to study the parameters necessary for welding pipe and the properties and microstructure of welds in API 5L X52 and X60 pipe. In later phases of the program, the welding of 12 in. (300 mm) diameter pipe will be studied.

The process has not been explored for underwater welding, but it should be pressure insensitive. The greater heat sink of a water environment would require higher welding heat input (welding current) and would quench the completed weld. A tempering treatment by means of a lower current pulse applied after the weld is made would soften any hard microstructure. This is a one-shot process that would be mechanized or automated, eliminating the need for manual welding skills.

The primary drawback could be in the area of equipment. The generator must be located close to the welding site as the high welding current cannot be conducted over any significant distance without high resistive losses. Whether the generator and its driving motor could be satisfactorily packaged for either wet or dry application must be explored. The welding process itself should be usable either wet or dry. Other questions relate to the tolerances for the machined pipe faces: how and where to perform the machining, if water on the joint mating surfaces would create any problems, whether the process would be applicable only to original construction of pipelines or whether it could be used for repair operations, whether any part configurations other than pipes could be welded, and whether the upset material must be removed after welding, particularly on the inside of pipe welds.

Friction Welding

Friction welding is a one-shot solid-state process, so no melting occurs during the welding operation, no hydrogen is generated to be absorbed by the weld, and no electrical power (in the conventional sense) is needed to heat the joint faces. Cooling rates may be slow enough that a hard HAZ will not be created. There are no known pressure effects on the welding process, so it could be used equally for shallow- and deep-water welding. Friction welding is a one-shot process that makes a complete weld in a matter of a few minutes or even seconds for smaller parts. Certain welds require removing the flash that forms in the same manner as for flash-butt welds.

The Navy currently uses wet friction welding to attach studs to hull steel. Arc-stud welding once was investigated for this application but arc stability problems, very rapid cooling effects, and the generation of hydrogen made wet arc-stud welding underwater impractical. Friction stud welding has progressed to the point that underwater welding apparatus is commercially available. The Navy also has initiated an investigation of the feasibility of friction surfacing underwater.

In its conventional configuration, friction welding is used on land for welding cylindrical parts (pipe and tubing) end-to-end. This process has been proposed for lay-barge used for pipeline construction, and it should be usable for the same application under water. Since individual lengths of pipe are too long to be rotated, short rings or pups are rotated between the stationary pipes and the two ends of the rings are welded simultaneously to the pipe ends. Tie-ins and repairs (replacing a damaged pipe section) could be made by the same technique.

Interest also is being shown in friction-stir and taper-stitch welding and friction hydro pillar processing (FHPP) both for repair and initial fabrication. However, friction-stir welding has been investigated only for welding aluminum, and its application to welding steel or other metals is, as yet, unknown. Taper-stitch welding and FHPP might be useful for repairing corrosion pits for filling holes or other localized voids.

Friction welding does not require complex apparatus although the equipment will be bulky, especially for pipe welding, simply because of the power requirements and the need to exert grasping pressure between the apparatus and the parts being welded and for exerting axial welding force. Equipment for welding pipe may be usable only on sea bottom simply because of its size. Equipment for taper-stitch welding and FHPP would be much smaller; it could almost be considered portable. This latter equipment could be used for making repairs to existing structures.

Friction welding can be performed in either a wet or dry environment although there may be equipment operation problems when the equipment is exposed to the water. Smaller welding equipment, such as for stud welding, has be enclosed in a waterproof housing with rotating parts operating through a seal. This technique would not be practical for larger equipment; large dry habitats may be required for friction welding larger objects.

In spite of the apparatus limitations, the distinct advantages of friction welding make it a process for consideration for both wet and dry welding.

Explosive Welding

Explosive welding has been used extensively for cladding materials and for welding parts that can utilize a lap joint. The parts are assembled with a precalculated space between the faying surfaces. An explosive is placed on the outer surface of one or both of these parts and detonated. The parts are forced together with such a high level of energy that the metal at the interface flows and a metallurgical bond is formed between the parts. Material combinations that are unweldable by fusion processes can be explosively welded without the formation of brittle intermetallic compounds. It is another one-shot solid-state welding process.

The process can be used for wet underwater welding and it has been applied in the attachment of lifting lugs to a device in 1000 ft. (300 m) of seawater [Ref. 8]. A technique also was developed for joining pipes end-to-end underwater [Ref. 9]. A bell and spigot joint configuration was used; the pipe end containing the female portion of the joint had to have a much thicker wall than the balance of the pipe and contained machined annular cavities into which the end of the male pipe was expanded by the internal explosive charge. An external annular anvil was used to prevent bulging of the joint from the internal explosive force. Because of the expense associated with this type of joint, there is no known practical application of this technique.

Explosive welding has been proven to be an effective joining process for the construction of large diameter cross-country transmission pipelines. This process was used in the construction of about 30 miles (48 km) of 30 in. (765 mm) diameter 5LX-60 pipeline in Canada. A tapered bell-and-spigot joint was used, but the female portion of the joint was formed by a hydraulic expander at the field site; no machining was required and the pipe wall was of uniform thickness. Both external and internal explosive charges were used and were detonated simultaneously so no backing anvil was required. The joint-to-joint times for this application were equal to and occasionally better than similar times for conventional arc welding construction. The properties of the joints met all of the requirements of API 1104.

Explosive welding is unique in that it has no moving parts nor is there a need for any specialized equipment. Placement of the explosive and the spacing of the parts is critical but gages and fixtures can be devised to accomplish this, even remotely. As with friction welding, no melting or hydrogen formation occurs and the welds do not have a HAZ so there are none of the usual metallurgical problems. The effect of pressure has not been investigated but it would appear that, if a problem, it could be overcome through proper sizing of the explosive package. The process should be considered only for wet welding, although some current cladding operations by a German company are conducted inside an explosive containment vessel. Containing the blast in such a dry vessel under water would be impractical, however.

This is a one-shot process that could be used both for original construction and repair operations (attachment of sleeves, pads, or parts having other configurations). No unusual skills would be required from the diver; the set-up operation could be done remotely using a robot. No specialized equipment would be required other than manipulators and placement gages. Joint preparation would be required, but this usually would entail only cleaning and smoothing; no machining would be necessary.

Obviously, there are many factors relative to the use of explosive welding underwater that must be considered before it can be accepted as a practical underwater welding process. What would be the potential damage to adjacent structures or pipelines? Would there be significant environmental effects? What would be the fit-up and explosive placement problems? The advantages are intriguing enough that this process should be considered a candidate for deep-water welding.

Conclusions

The present pattern of investigation and development of processes, consumables, and techniques for underwater welding has lacked coordination and direction. A suggested plan for a more systematic course of development would be to categorize and coordinate the areas of development to provide a more efficient utilization of development resources. A development program must include the following interrelated categories:

1. Conduct a comprehensive review and critique of these and other new welding processes and technologies to fully investigate their potential for underwater use.

2. Based on Step 1, select the most promising processes for further investigation and development.

3. Demonstrate and provide proof of concept for the selected processes based on:

    a. Weld quality: soundness of weld and HAZ, microstructure, repeatability, and inspectability.

    b. Structural performance of welds; create a data base of static strength, fracture strength, fatigue strength, and corrosion resistance.

    c. Evaluation of processes from the standpoint of operation in a wet and/or dry environment.

    d. Identification of specific areas needing further development and the potential success of the process for underwater application.

4. Educate the diving community on the developing processes through workshops, seminars and conferences.

5. Develop recommended procedures and specifications based on data obtained through use and qualification of selected processes, technical development, experience of users and operators and input from regulating bodies.

6. Identify sources of development funding that could include fabricators, regulators, oil companies, equipment producers, federal agencies and international sources.

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Table 1. Features of Advanced Processes for Underwater Welding (Continued)

Process	Technique	Wet/Dry	Depth Limit, m (ft)	Applications	Materials	Process Characteristics		Development Cost	Technical Risk	Economic Risk	Development Time, Years
						Advantages	Disadvantages				
Resistance	Flash butt	Dry wet (?)	>1,000 (3,300)	- Butt joint-bars or tubulars - New construction only	- All steels	- One shot (2-3 min.) - Narrow weld - Solid-state weld - Mechanized only	- Massive equipment - Expensive equipment - Post weld flash removal	High	Low (tubes) High (pipe)	High	5-10
	Homopolar	Dry wet (?)	>1,000 (3,300)	- Butt joint-bars or tubulars - New construction only	- All steels	- One shot (<10 sec.) - Narrow weld - Solid-state weld - Mechanized only	- Massive equipment - Post weld flash removal	High	Low (tubes) High (pipe)	High	5-10
Friction	Conventional and radial	Wet or dry	>1,000 (3,300)	- Butt joint - New construction or repair (pipe)	- All steels - Ti alloys - Al alloys - Dissimilar materials	- One shot process - Solid-state weld - Mechanized only	- Massive equipment - Post weld flash removal	High	Low	Medium	3-5
	Taper stitch	Wet or dry	>1,000 (3,300)	- Attachments - New construction or repair	- All steels - Ti alloys - Al alloys - Dissimilar materials	- One shot process - Solid-state weld - Small equipment - Mechanized or manual	- Post weld flash removal	Low	Low	Low	1-3
	FHPP	Wet or dry	>1,000 (3,300)	- Repair of pits or holes - Plug work	- All steels - Ti alloys - Al alloys - Dissimilar materials	- One shot process - Solid-state weld - Small equipment - Mechanized only		Low	Low	Low	1-3
Explosive	Bell/spigot	Wet	>1,000 (3,300)	- Joining pipe or tube - New construction only - Lap joint only	- All steels - Ti alloys - Al alloys - Dissimilar materials	- One shot process - Very fast (< 1 sec) - Minimal equipment - Mechanized or manual set up	- Potential damage to adjacent structures - Explosive safety hazard - Auxiliary equipment for forming bell and spigot joint	Medium	Medium	Medium	1-3
	Sleeve/patch	Wet	>1,000 (3,300)	- Repairs - Attachments - Lap joint only	- All steels - Ti alloys - Al alloys - Dissimilar materials	- One shot process - Very fast (< 1 sec) - Minimal part preparation - Minimal equipment - Mechanized or manual set up	- Potential damage to adjacent structures - Explosive safety hazard	Low	Low	Low	1-3

Table 1. Features of Advanced Processes for Underwater Welding

Process	Technique	Wet/Dry	Depth Limit, m (ft)	Applications	Materials	Process Characteristics: Advantages	Process Characteristics: Disadvantages	Development Cost	Technical Risk	Economic Risk	Development Time, Years
Arc	Activated GTA	Dry	500 (1,650)	- Butt joint - Fillet weld - New construction and repair	- All steels - Ti alloys - Al alloys - Clad materials	- Increase penetration re: GTA - Increased welding speed re: GTA - Improved arc stability mechanized or manual	- Fumes (?) - Corrosion caused by activated coating (?)	Low	Medium	Low	1-3
	Microwave plasma	Wet & dry	1,000 (3,300)	- Butt joint - Fillet weld - New construction and repair	- All steels - Ti alloys - Al alloys - Clad materials	- No electrode - Increased penetration re: arc - Increased welding speed re: arc - Mechanized or manual	- Unknown power requirements - Requires plasma gas - Hydrogen pickup in wet welding	Low	Medium	Medium	3-5
Laser	CO_2	Dry (wet?)	>1,000 (3,300)	- Butt joint - Fillet weld - New construction and repair	- All steels - Ti alloys	- Deep penetration (~1") - Narrow and HAZ - Mechanized only	- Massive equipment - High equipment cost - Critical fitup - Laser must be within 50 ft. of weld sensitive equipment	High	High	High	5-10
	YAG	Dry (wet?)	>1,000 (3,300)	- Butt joint - Fillet weld - New construction and repair	- All steels - Ti alloys	- Good penetration (no. 5") - Narrow weld and HAZ - Laser can be up to 500 ft. from weld - Mechanized only	- Critical fitup	High	High	Medium	3-5
	YAG arc (GTA, GMA, FCA)	Dry & wet	>1,000 (3,300)	- Butt joint - Fillet weld - New construction and repair	- All steels - Ti alloys - Al alloys (?)	- Improved arc stability - Increased welding speed re: arc alone - Mechanized only	- Critical fitup (?) - Complicated welding of two processes	High	Medium	Medium	3-5
Electron Beam	In air	Dry	500 (1650) (?)	- Butt joint - Fillet weld - New construction and repair	- All steels - Ti alloys - Al alloys (?)	- Narrow weld and HAZ - Could be portable - Mechanized or manual	- Critical fitup - Limited penetration - Penetration sensitive to water depths - X-rays - Sensitive equipment	High	Medium	High	5-10

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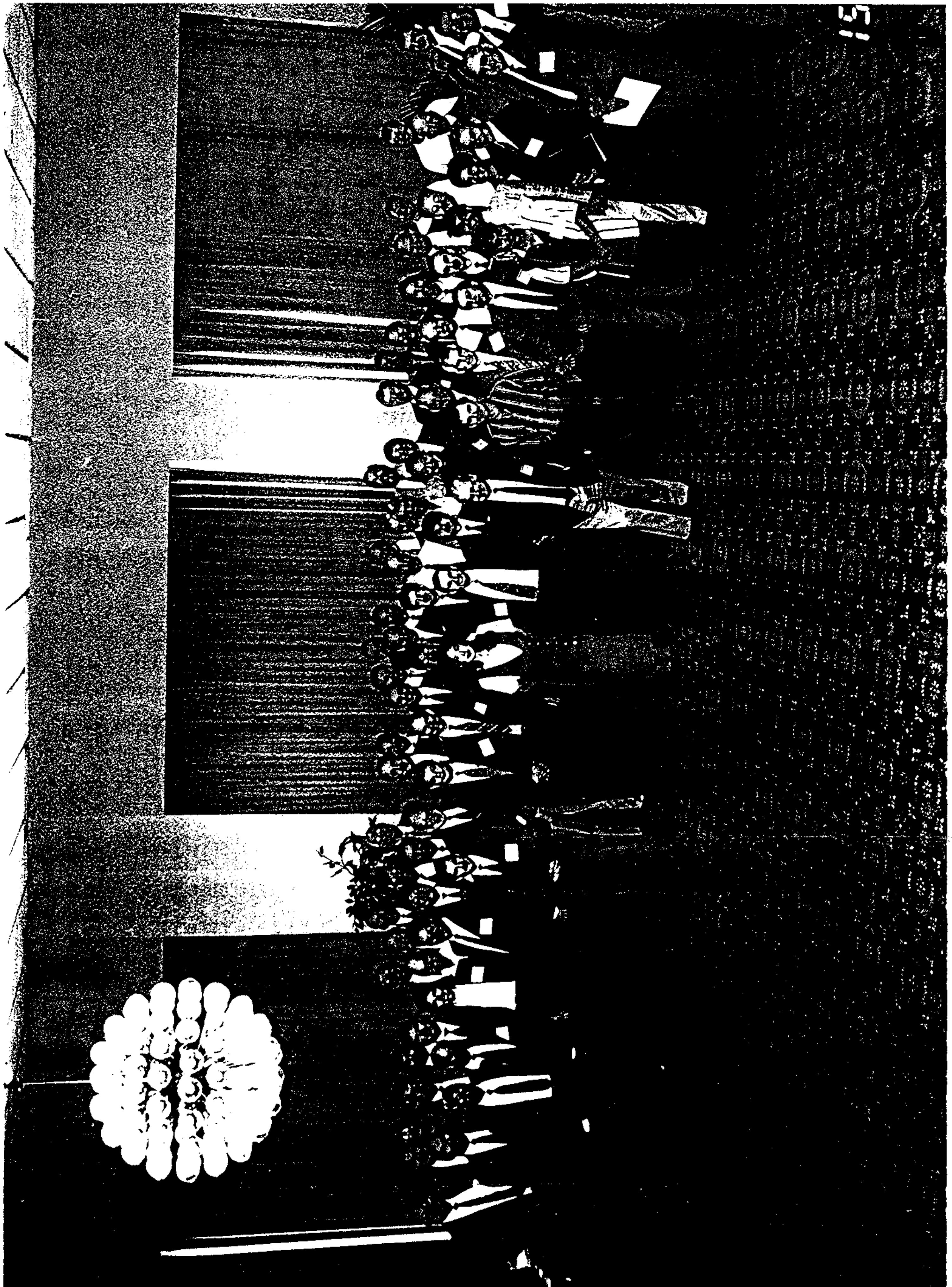

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